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DESIGN OF ALTERNATING-CURRENT APPARATUS
ELECTRIC TRANSMISSION
LINE CONSTRUCTION
SWITCHBOARDS AND SWITCHBOARD APPLIANCES
POWER TRANSFORMATION AND MEASUREMENT

SCRANTON:
INTERNATIONAL TEXTBOOK COMPANY
13C

PRINTED IN THE UNITED STATES

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PREFACE

The International Library of Technology is the outgrowth of a large and increasing demand that has arisen for the Reference Libraries of the International Correspondence Schools on the part of those who are not students of the Schools. As the volumes composing this Library are all printed from the same plates used in printing the Reference Libraries above mentioned, a few words are necessary regarding the scope and purpose of the instruction imparted to the students of—and the class of students taught by—these Schools, in order to afford a clear understanding of their salient and unique features.

The only requirement for admission to any of the courses offered by the International Correspondence Schools, is that the applicant shall be able to read the English language and to write it sufficiently well to make his written answers to the questions asked him intelligible. Each course is complete in itself, and no textbooks are required other than those prepared by the Schools for the particular course selected. The students themselves are from every class, trade, and profession and from every country; they are, almost without exception, busily engaged in some vocation, and can spare but little time for study, and that usually outside of their regular working hours. The information desired is such as can be immediately applied in practice, so that the student may be enabled to exchange his present vocation for a more congenial one, or to rise to a higher level in the one he now pursues. Furthermore, he wishes to obtain a good working knowledge of the subjects treated in the shortest time and in the most direct manner possible.

In meeting these requirements, we have produced a set of books that in many respects, and particularly in the general plan followed, are absolutely unique. In the majority of subjects treated the knowledge of mathematics required is limited to the simplest principles of arithmetic and mensuration, and in no case is any greater knowledge of mathematics needed than the simplest elementary principles of algebra, geometry, and trigonometry, with a thorough, practical acquaintance with the use of the logarithmic table. To effect this result, derivations of rules and formulas are omitted, but thorough and complete instructions are given regarding how, when, and under what circumstances any particular rule, formula, or process should be applied; and whenever possible one or more examples, such as would be likely to arise in actual practice—together with their solutions—are given to illustrate and explain its application.

In preparing these textbooks, it has been our constant endeavor to view the matter from the student's standpoint, and to try and anticipate everything that would cause him trouble. The utmost pains have been taken to avoid and correct any and all ambiguous expressions—both those due to faulty rhetoric and those due to insufficiency of statement or explanation. As the best way to make a statement, explanation, or description clear is to give a picture or a diagram in connection with it, illustrations have been used almost without limit. The illustrations have in all cases been adapted to the requirements of the text, and projections and sections or outline, partially shaded, or full-shaded perspectives have been used, according to which will best produce the desired results. Half-tones have been used rather sparingly, except in those cases where the general effect is desired rather than the actual details.

It is obvious that books prepared along the lines mentioned must not only be clear and concise beyond anything heretofore attempted, but they must also possess unequaled value for reference purposes. They not only give the maximum of information in a minimum space, but this information is so ingeniously arranged and correlated, and the

indexes are so full and complete, that it can at once be made available to the reader. The numerous examples and explanatory remarks, together with the absence of long demonstrations and abstruse mathematical calculations, are of great assistance in helping one to select the proper formula, method, or process and in teaching him how and when it should be used.

The first portion of this volume contains an exceptionally distinct and intelligible treatise on the complex problems relating to the design of alternating-current apparatus. The correct proportions and relative location of the different parts of the machines are clearly set forth and illustrated by numerous figures showing the details of the construction. The design of alternators, motors, and transformers is fully discussed. The various systems of transmitting electrical energy, and the methods used in calculating the size of wires, and installing the wires for overhead and underground transmission systems, are described in great detail, and complete wire data tables are furnished. The treatment of switchboards in this volume is very complete and is superior to anything yet published. The recent styles of oil switches, circuit-breakers, measuring instruments, etc. are fully explained and illustrated, and their location indicated on the switchboard diagrams. Under the heading Power Transformation and Measurement, a very clear treatise is given of the installation of transformers and substations and the methods of power measurements.

The method of numbering the pages, cuts, articles, etc. is such that each subject or part, when the subject is divided into two or more parts, is complete in itself; hence, in order to make the index intelligible, it was necessary to give each subject or part a number. This number is placed at the top of each page, on the headline, opposite the page number; and to distinguish it from the page number it is preceded by the printer's section mark (§). Consequently, a reference such as § 16, page 26, will be readily found by looking along the inside edges of the headlines until § 16 is found, and then through § 16 until page 26 is found.

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DESIGN OF ALTERNATING-CURRENT APPARATUS

(PART 1)

INTRODUCTION

1. In the design of alternating-current generators, motors, and transformers, the principles given in the theory of alternating currents are applied in much the same manner as are those relating to direct currents in the design of direct-current machinery. For example, calculations regarding the magnetic circuit and the determination of the ampere-turns required to set up a given magnetic flux through a given path are made in practically the same manner in both classes of apparatus. A great many of the mechanical details are also similar, and a thorough understanding of the design of direct-current machinery goes far toward making clear the corresponding design of alternating-current apparatus.

In the design of electrical machinery, either direct or alternating, the production of a good and economical design depends to a great extent on the experience of the designer and on data obtained from tests with similar machines. Thus, for a given output, a machine designed by one engineer may have very good ventilation, so that a small armature can be used without exceeding the specified temperature limits, but the regulation may be comparatively poor. Another designer may use a larger armature with lower

armature resistance, inductance, and reaction and a stronger field, thus giving better regulation. There is therefore considerable choice in the matter of dimensions, and the best design commercially is the one that will give the best electrical performance at the lowest cost consistent with substantial construction and reliable operation.

ALTERNATORS

LIMITATIONS OF OUTPUT

REGULATION AND HEATING LIMITS

2. In direct-current dynamos, the output is limited by two factors; namely, heating of the armature and sparking at the brushes. An alternator has no commutator, hence sparking cannot enter as a limiting factor. The various losses in the armature core and coils cause heating, as in direct-current generators, and there is also the limit set by the required regulation of the alternator. Both heating and regulation must therefore be kept in view when working out the design of a machine.

3. Regulation.—If the self-induction of the armature of an alternator is very high, a considerable part of the generated electromotive force may be required to force the current through the armature, thus reducing the electromotive force at the terminals. Also, under certain conditions, the armature currents may exert a powerful demagnetizing effect on the field, thus weakening it and causing a falling off in the pressure. As a result of these effects of armature self-induction and armature reaction, the terminal voltage falls off as the current taken from the machine increases, assuming that the field excitation and speed are held constant.

4. On the other hand, when the current is thrown off, the terminal voltage rises. By **regulation** is meant the

percentage that the voltage increases when the full-load current is thrown off; and, since it is essential in practical operation that the voltage variation shall not exceed a certain amount, alternators nearly always have to be built under a certain guarantee as to regulation. For example, it might be specified that a 2,200-volt alternator should have a regulation of 6 per cent., meaning that when full load is thrown off, the voltage should not rise more than $2,200 \times .06 = 132$ volts; that is, the generator pressure should not rise above 2,332 volts. The percentage always refers to the full-load voltage, because full load is considered the normal operating condition of the machine. In case the regulation is poor or if the load is carried beyond the allowable limit, it may be impossible to maintain the voltage, even with the maximum field current obtainable.

5. Regulation Dependent on Character of Load. The regulation depends greatly on the kind of load that the machine carries. The drop in pressure might be comparatively small on a non-inductive load of lights, and yet so great on an inductive load of motors as to make it impossible to keep up the voltage. A statement of the regulation should always include the power factor of the load on which the machine operates. If the regulation on a non-inductive load is, say, 8 per cent., it may be 19 per cent. on a load with a power factor of .8, and still greater on loads having lower power factors. Modern revolving-field alternators usually give a regulation of from 4 to 9 per cent. on non-inductive loads, and from 12 to 24 per cent. on inductive loads with power factors of from .8 to .85.

6. Heating.—In most large slow-speed alternators of the revolving-field type, the ventilation is so good that full load can be carried with a rise in temperature well within the specified limit, which is usually from 35° to 45° C. above the surrounding air; the limiting factor for the output of such machines is therefore the voltage regulation. With high-speed machines, such as alternators for direct connection to steam turbines, where the armature is comparatively small

in diameter and ventilation not so thorough, the output may be limited by heating rather than by regulation, unless artificial means of cooling by fans or blowers are used.

HEATING OF ALTERNATOR ARMATURES

7. Practically all modern alternators are of the revolving-field type, with the stationary armature arranged externally to the field. The core is constructed with numerous ducts, or air passages, between the laminations; the projecting poles on the revolving field act like fan blades and force powerful currents of air through the ducts and the windings. The ventilation is thus very thorough, being particularly so in alternators of large diameter for direct connection to steam engines. In these machines, the whole construction is very open, and large, temporary overloads can be carried without injurious heating. The final temperature that an armature attains depends not only on the actual amount of energy wasted in it, but also on the readiness with which the heat can be imparted to the surrounding air. The temperature will keep on increasing until the heat is dissipated as fast as it is generated, the rise in temperature necessary to bring about a steady temperature depending on the construction of the armature. A well-ventilated armature can dissipate more heat per degree rise than one that is poorly ventilated. By careful attention to ventilation, builders have been able to reduce the size of machine for a given output, and in many modern designs the size could be still further reduced so far as heating is concerned. A reduction in size, however, would interfere with the regulation—the other limiting factor that must always be kept in mind.

8. Armature Losses.—The losses in the armature of an alternator are of the same character as those in a direct-current machine; namely, iron loss, consisting of hysteresis and eddy-current loss, and copper, or $I^2 R$, loss. The hysteresis and eddy-current loss is practically constant at all loads, while the copper loss increases as the square of the current, and becomes very large if the machine is heavily overloaded.

If an alternator is run on open circuit with its field fully excited, there is no loss in the armature conductors because there is no current flowing; but the mass of iron in the core is subjected to alternating magnetization by the rotating field magnet, and consequently there is a core loss, or iron loss, due to hysteresis and eddy currents. This core loss will cause the armature to heat until the rise in temperature is sufficient to radiate the losses. When the machine is loaded, there is, in addition to the iron loss, an I^2R loss in the conductors due to the current and the resistance of the conductors. The temperature of the armature then increases further until a point is reached where the total heat is dissipated as fast as generated. If the alternator is overloaded, the I^2R loss becomes excessive, soon reaching a point where it would be unsafe to increase the load further.

What was said regarding the safe-heating limit of the insulating materials used for direct-current armatures applies even with greater force to armatures for alternators. It is bad practice to run alternators too hot, because sooner or later the insulation will be destroyed; also, as these machines are frequently wound for high voltages, any deterioration of the insulation is a serious matter.

9. Allowable Temperature Rise.—The final temperature that the armature attains under a given load depends on the temperature of the surrounding air. It is not safe to count on less than 25° C. for the average air temperature, because in engine rooms it frequently rises far above this. A fair rise in temperature may therefore be taken as from 70° to 90° F., or from 40° to 50° C. A common guarantee for alternators is that they will carry full load for 24 hours with a rise in temperature in no part exceeding 40° C. above surrounding air at 25° C., and that they will carry 25-per-cent. overload for 2 hours, following the run at full load, with a temperature rise not exceeding 55° C. The rise in temperature is sometimes forced as high as 60° or even 65° C., but this is sure to injure the machines in time and is only excusable in cases of emergency.

10. Relation Between I^2R Loss and Armature Surface.—It is difficult to make accurate calculations regarding the increase in temperature of an armature, but it is comparatively easy to form an idea as to whether there will be undue heating. Experience has shown that for machines of a given type there is more or less definite relation between the watts I^2R loss in the active armature conductors and the surface of the inner cylindrical face of the stationary armature. A simple formula for calculating the I^2R loss per square inch is the following:

$$W_t = \frac{K}{M_t},$$

in which W_t = watts I^2R loss per square inch of cylindrical armature surface;
M_t = number of circular mils per ampere in the armature conductor;
K = number of ampere-conductors per inch of inner periphery of armature.

This formula, first given by Prof. C. A. Adams, is derived as follows: In 1 inch of armature periphery there are K ampere-conductors; if the current in each conductor is i amperes, there are $\frac{K}{i}$ conductors per inch of periphery. Considering each of these $\frac{K}{i}$ conductors 1 inch long, the sum of the I^2R losses in them is the I^2R loss per square inch of armature surface. The hot resistance of 1 mil-foot of copper is very nearly 12 ohms, and of 1 mil-inch is 1 ohm. If M_t is the number of circular mils per ampere and i the number of amperes, then the area of a conductor is $M_t \times i$ circular mils. The resistance R of 1 inch of conductor is

$$\frac{\text{resistance of 1 mil-inch}}{\text{area in circular mils}} = \frac{1}{M_t \times i}$$

The I^2R loss in 1 inch of conductor is $\frac{i^2}{M_t \times i} = \frac{i}{M_t}$, and the combined losses W_t in the $\frac{K}{i}$ conductors in 1 inch of periphery is $\frac{K}{i} \times \frac{i}{M_t} = \frac{K}{M_t}$.

11. The quotient obtained from dividing the ampere-conductors per inch by the circular mils per ampere, that is, the watts I^2R loss per square inch of armature cylindrical surface, will usually lie between .4 and 1 for modern revolving-field alternators. For machines of moderate voltage, say 4,400 volts or lower, running at a moderate peripheral speed of 2,000 to 4,000 feet per minute, the quotient will usually be from .5 to .7. For high-voltage machines, the circular-mils allowance per ampere is usually large, because the heavily insulated coils do not dissipate their heat easily; therefore, liberal carrying capacity must be allowed. In these generators the watts per square inch may frequently be as low as .4. For exceptionally well-ventilated waterwheel-type alternators running at high peripheral speed—from 6,000 to 9,000 feet per minute—the value may be as high as .9 or 1. Where the field coils of induction motors are distributed in a large number of slots on the stationary member, and where the room available for the conductors is more limited than in alternators, the circular mils per ampere in the stationary winding are usually less, and the I^2R loss per square inch correspondingly larger. If the motor as a whole is designed to secure free air circulation, the loss in the field winding may run as high as 1.1 or 1.2 watts per square inch without causing undue heating.

EXAMPLE.—In an alternator there are 96 slots with 20 conductors per slot arranged around the circumference of an armature 70 inches in diameter. The current in a conductor is 50 amperes and the cross-section of the conductor is 30,000 circular mils. How many watts I^2R loss are liberated per square inch of cylindrical armature surface?

SOLUTION.—Inside circumference of armature = 3.1416 × 70 = 220 in., approximately; total number of conductors = 96 × 20 = 1,920; total ampere-conductors = 1,920 × 50 = 96,000; ampere-conductors per in. = K = 96,000 ÷ 220 = 436; and circular mils per ampere = M_t = 30,000 ÷ 50 = 600. Applying the formula,

$$W_t = \frac{436}{600} = .73 \text{ watt, nearly. Ans.}$$

This is a fair value for the I^2R loss per square inch, and it alone is not sufficient to cause the machine to overheat.

CORE LOSSES

12. Because of the higher frequency of the magnetic reversals, the **core losses** in alternating-current machinery are usually greater than in direct-current machinery of corresponding size. In alternators, the core losses are usually much greater than the I^2R loss, and consequently the no-load rise in temperature may be considerable.

By careful selection of the iron used for armature cores and by annealing after punching, the hysteresis loss can be kept within reasonable limits. This loss can be calculated with a fair degree of accuracy, but calculating the eddy-current loss is practically impossible. To keep down the eddy currents, all armature punchings used in alternating-current machinery must be carefully japanned or varnished, and in building up the core, special pains must be taken to avoid connecting the punchings by slot filing. If necessary, layers of thin paper should be placed at intervals in the core. The laminations should not be clamped between the end plates any tighter than is necessary to hold the core securely together. Excessive pressure on the stampings makes a marked increase in the core loss, especially if the varnishing has not been carefully done. In building up the cores, these precautions must not be neglected, or abnormally large core losses will result.

Again, when an alternator field is fully excited and rotated within the armature, numerous stray currents are generated in any metal parts that carry a varying magnetic flux; for example, the teeth in the armature cause variations in the flux across the pole faces and pole-face eddy currents are set up. With poles made of laminations, these currents can be limited, but there is always some loss due to this cause. Also in the armature teeth, in which the magnetic flux is continually changing and in which certain parts of the iron are sometimes highly saturated, the eddy currents may cause considerable loss.

On account of these effects, the core loss in an alternator is much larger than in a similar amount of iron worked at

the same average magnetic density in, say, a transformer core. The loss is also greater than would be indicated by a hysteresis test on the iron by means of the wattmeter method.

13. In Fig. 1, curve AA, plotted from data taken by means of wattmeter tests, shows the core loss in armature

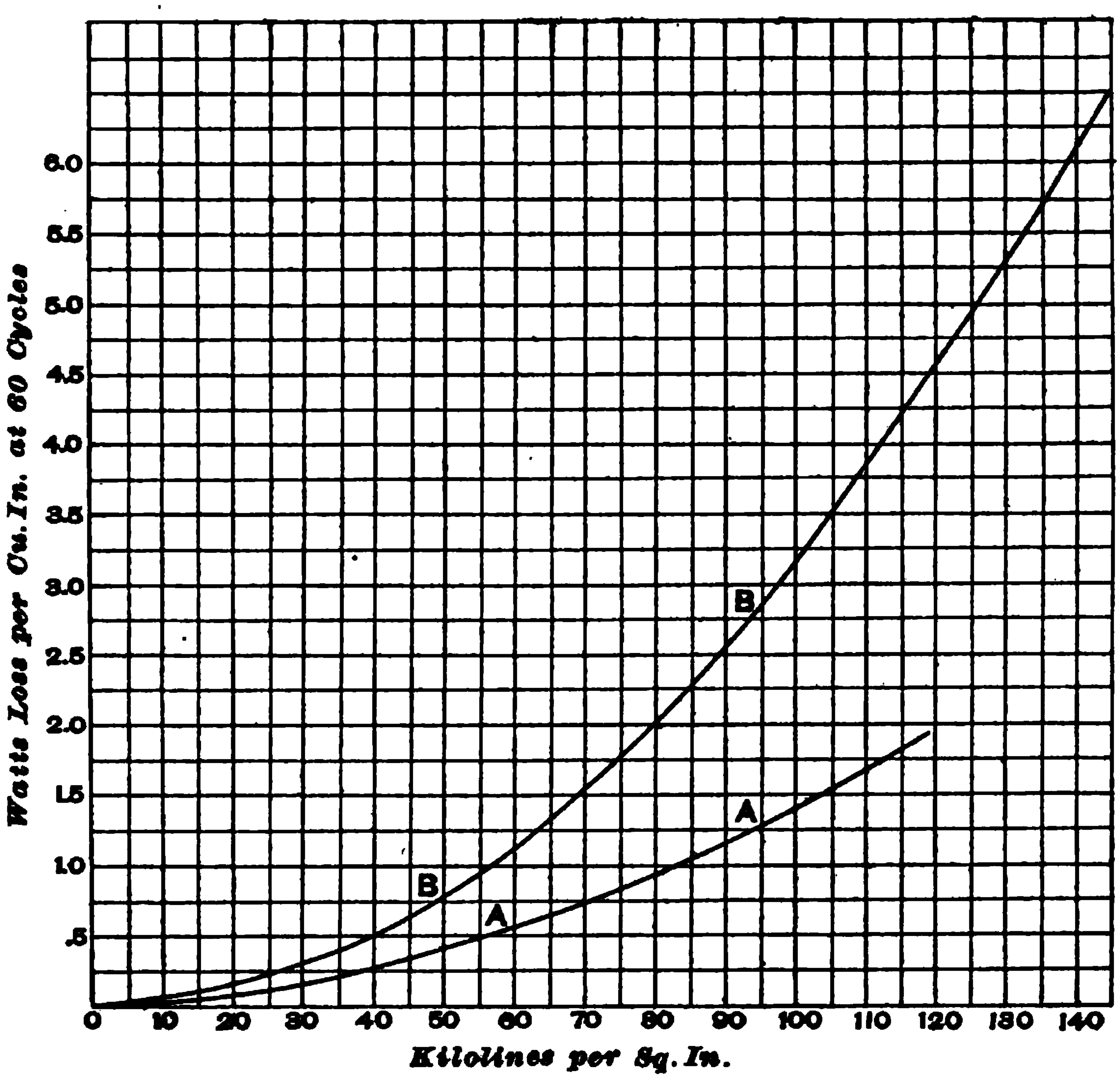


Fig. 1

steel of average quality when used in transformers. This curve shows the relation between the watts loss per cubic inch at 60 cycles and the magnetic density in *kilolines* (thousands of lines) per square inch. This curve will give satisfactory results when used for estimating the loss in the cores of transformers. Curve BB gives the approximate loss per cubic inch in the same grade of iron when used for alternator armature cores and other cores worked under similar

conditions. The loss is from two to two and one-half times as great as that shown by AA, but it represents results as shown by tests on a large number of machines.

The curves are drawn for 60 cycles, but can be used for other frequencies by multiplying the result, as taken from the curve, by the actual frequency and dividing by 60. In making core-loss calculations, separate estimates must be made for the core proper and the teeth, and the two results added together; this is necessary because the magnetic density in the teeth is usually much greater than in the core.

EXAMPLE.—The volume of the teeth of a 60-cycle alternator core is 2,000 cubic inches, and the magnetic density in them is 90,000 lines per square inch. (*a*) What is the core loss in the teeth? (*b*) What would be the core loss at 25 cycles? (*c*) What would be the core loss at 60 cycles in a transformer core having the same volume and worked at the same density?

SOLUTION.—(*a*) For a density of 90,000 lines per sq. in., the loss, according to curve BB, Fig. 1, is approximately 2.5 watts per cu. in.; hence, the total loss at 60 cycles is $2{,}000 \times 2.5 = 5{,}000$ watts. Ans.

(*b*) At 25 cycles, the loss would be $2.5 \times \frac{25}{60} \times 2{,}000 = 2{,}083$ watts. Ans.

(*c*) In a 60-cycle transformer core, the loss would be as shown by curve AA; that is, 1.15 watts per cu. in., or $2{,}000 \times 1.15 = 2{,}300$ watts, total. Ans.

HEATING OF REVOLVING FIELDS

14. The **revolving fields** of modern alternators usually consist of a number of poles attached to the rim of a field spider, each pole carrying a magnetizing coil made of copper strip wound on edge, as explained more fully under mechanical construction of alternators. The edge of the bare copper strip is exposed to the air, and if the peripheral speed is high, a large amount of heat can be dissipated with but a moderate rise in temperature. The field coils should be designed so that they will stand the current set up by the maximum exciter voltage without overheating, and it is therefore important to know approximately how many watts can be dissipated per square inch of coil surface.

Table I shows the number of watts per square inch corresponding to temperature increases of 40° and 55° C. for

peripheral speeds ranging from 1,000 to 9,000 feet per minute. The area of the coil on which these figures are based is taken as the outside surface, assuming the coil to have square corners; that is, no allowance is made for rounded corners in estimating the watts per square inch. With a peripheral speed of 9,000 feet per minute and 55° C. rise, 5.17 watts per square inch can be dissipated from the rotating field coils, while the stationary field coils used on direct-current machines could not dissipate much over .5 watt per square inch with the same temperature rise. This shows

TABLE I

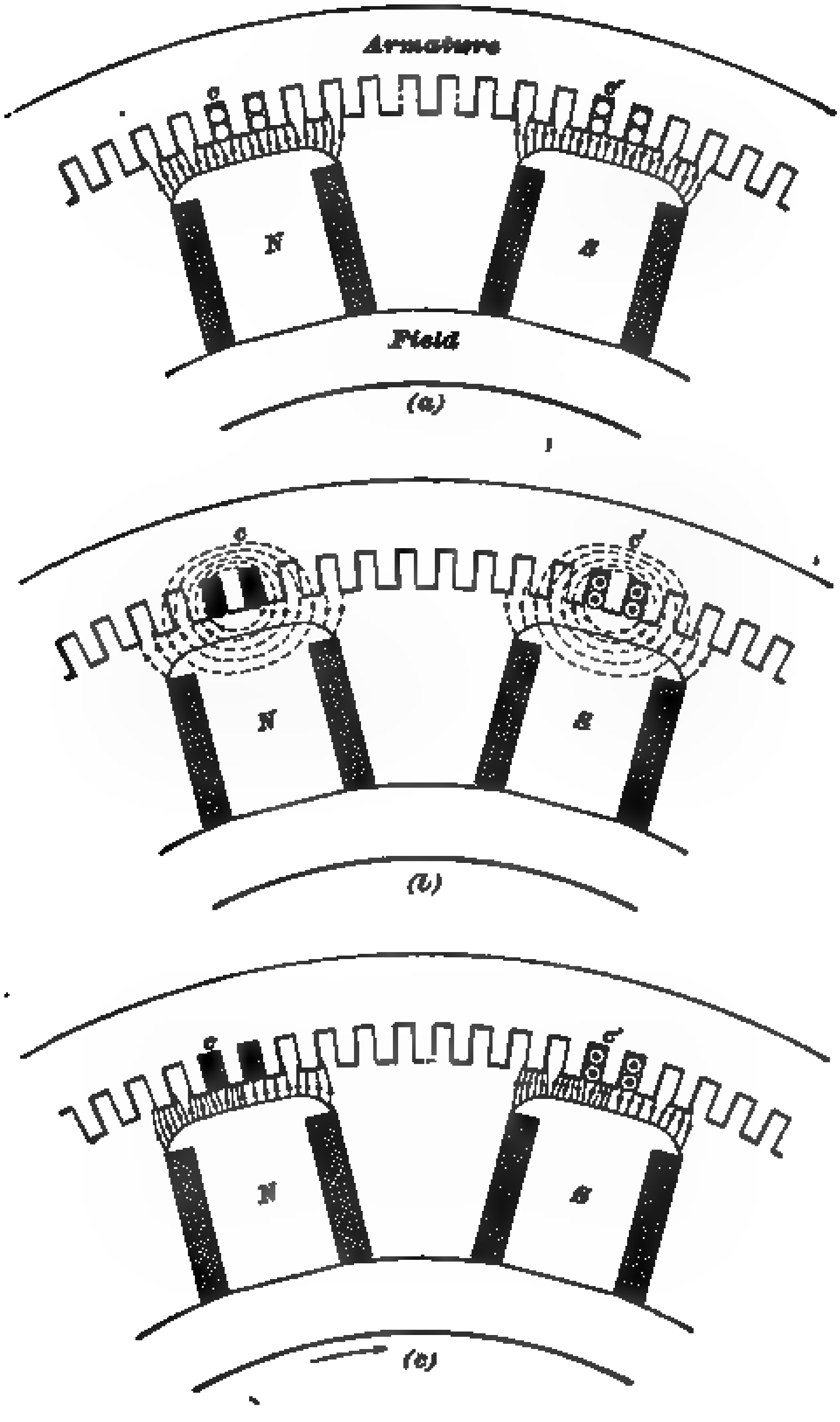
RELATION BETWEEN WATTS DISSIPATED AND PERIPHERAL SPEED OF REVOLVING FIELDS

Peripheral Speed Feet per Minute	Watts per Square Inch	
	40° C. Rise	55° C. Rise
1,000	.9	1.24
2,000	1.55	2.1
3,000	2.1	2.85
4,000	2.5	3.52
5,000	2.9	4.12
6,000	3.33	4.57
7,000	3.57	4.9
8,000	3.7	5.07
9,000	3.8	5.17

the great difference caused by effective ventilation and also by the use of edgewise winding that exposes the copper directly to the air.

ARMATURE REACTION

15. Armature reaction plays an important part in the design of direct-current machinery, since, if it is excessive, the magnetic field may be so distorted or weakened as to cause bad sparking at the commutator. Sparking cannot occur in an alternator, but the weakening of the field will



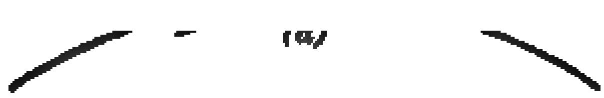


FIG. 2

cause a drop in voltage and hence affect the regulation. In order to estimate the regulation, it is therefore necessary among other things to know the demagnetizing effect that the armature exerts on the field.

In Fig 2 let *N*, *S* represent two poles of a revolving field and *c*, *c'* two groups of conductors forming a coil in the armature slots. With no current flowing in the armature and with the fields excited, the magnetic field in the air gap will be nearly uniform over the pole faces, as indicated in (*a*) by the lines with arrowheads. The flux then passes from a north pole *N* into the armature, and from the armature into a south pole *S*. In (*b*), the fields are unexcited, but current is sent through the armature from some outside source, so as to flow downwards through conductors *c* and upwards through conductors *c'*. These armature currents will set up magnetic lines of force, as indicated by the circular dotted lines.

16. With the fields excited as in (*a*) and rotated so as to set up current in *c*, *c'* in the same direction, as in (*b*), the fields shown separately in (*a*) and (*b*) will be superimposed, with the result that the flux is made more dense at the left-hand side of the poles and thinned out at the right-hand side, as shown in (*c*); this is seen by comparing the directions of the arrowheads in (*a*) and (*b*), noting that the directions of the two fields are opposed at the right-hand sides of the poles. In (*c*), assuming that the alternating current is in phase with the induced electromotive force, the current in the conductors is at the maximum value the instant the poles are in the position shown, because the conductors are then opposite the pole centers. Under these conditions the armature reaction simply distorts the field, but does not produce any appreciable weakening of it unless, as is not usual, the crowding of the lines causes such a high degree of saturation in the teeth as to choke back some of the lines.

If, however, owing to self-induction, the current in the armature lags behind the induced electromotive force, the magnetic effect of the armature currents tends to weaken

the field. In (d) is indicated the extreme case where the armature current lags 90° behind the electromotive force; the current in conductors c, c' does not reach its maximum until pole N has passed around to the point shown. The induced electromotive force in c, c' at this instant is zero, but on account of the 90° lag, the armature current tends to form poles N', S' that are squarely opposed to those on the field, and the armature thus exerts a powerful demagnetizing action that, if not offset by a corresponding increase in the field excitation, will cause a decided weakening of the field and a drop in voltage.

The demagnetizing effect of the armature current varies as the sine of the angle of lag of the armature current behind the electromotive force. When the current and the electromotive force are in phase, the angle of lag is zero, its sine is zero, and there is no demagnetizing action. When the lag is 90°, the sine is 1 and the demagnetizing action is greatest; that is, the whole armature ampere-turns are directly opposed to those of the field. For intermediate angles of lag, the demagnetizing effect varies between these two extremes. If the current could be made to lead the electromotive force, the armature would magnetize the field instead of demagnetizing it, but this condition is never met in ordinary operation.

17. Armature Ampere-Turns.—The following formula gives the approximate value of the armature ampere-turns on a polyphase alternator, and is useful in making preliminary calculations where the exact dimensions of the poles are not known:

$$\text{Armature ampere-turns per pole} = .707\, m\, T_{pp}\, I_p, \qquad (1)$$

in which m = number of phases;

T_{pp} = turns per pole, per phase;

I_p = current in armature turns.

To determine the approximate value of the demagnetizing action of the armature ampere-turns, the following formula may be used:

$$\text{Demagnetizing ampere-turns per pole} = .707\, m\, T_{pp}\, I_p \sin a, \qquad (2)$$

in which a is the angle of lag between the current and the induced electromotive force, or the angle by which the center line of the pole is displaced from the conductors when the current in the latter reaches its maximum value.

NOTE.—Since the turns per pole per phase equals the turns per pole divided by the number of phases, or $T_{pp} = \frac{T_p}{m}$, the expression $m\,T_{pp}$ reduces to T_p, which could be used in place of $m\,T_{pp}$ in formulas **1** and **2**. The formulas, however, are given in their usual form.

When the lag is 90°, as is very nearly the case when the alternator supplies a highly inductive load having a power factor under .2, sin a = 1, and the right-hand side of formula **2** becomes equal to the right-hand side of formula **1**; that is, all the armature ampere-turns tend to demagnetize the field.

EXAMPLE.—A 3-phase 12-pole alternator when fully loaded delivers 50 amperes per line. The armature is Y-connected and has 108 slots, each containing 20 conductors. (*a*) How many ampere-turns per pole are supplied by the armature at full load? (*b*) If the angle of lag between the current and the induced electromotive force is 30°, how many ampere-turns on the armature are opposed to the field?

SOLUTION.—(*a*) There are $108 \times 20 = 2{,}160$ conductors on the armature or $2{,}160 \div 12 = 180$ conductors per pole and 60 conductors per pole per phase. In formula **1**, $T_{pp} = \frac{60}{2} = 30$, and, since the armature is Y-connected, the current in the windings will be the same as the current per line. $I_p = 50$ and $m = 3$; hence,

armature ampere-turns $= .707 \times 3 \times 30 \times 50 = 3{,}182$, nearly. Ans.

(*b*) The angle of lag a in this case is 30°; hence,

demagnetizing ampere-turns per pole $= 3{,}182 \times \sin 30°$
$= 3{,}182 \times .5 = 1{,}591$. Ans.

18. Strictly speaking, however, the armature demagnetizing ampere-turns depend on the character of the armature winding and its relation to the poles. They also depend on the ratio of the breadth of pole face to the pole pitch (circumferential distance between centers of poles). The following formula, which includes these factors, is more complicated and more nearly correct than formula **2**, Art. **17**, and can only be applied after the style of winding and shape of poles for a given machine have been chosen.

Demagnetizing ampere-turns per pole

$$= .9\, m\, T_{pp}\, I_p\, k_w\, k_p \sin a,$$

in which m, T_{pp}, I_p and a have the same meaning as in formula **1**, Art. **17**; k_w is a coefficient depending on the arrangement of the armature winding; and k_p is a coefficient depending on the ratio $\frac{\text{pole arc}}{\text{pole pitch}}$.

The meaning of the coefficient k_w will be explained in connection with armature windings, but for convenience its values for the more common windings are here given. In case there is only one slot per pole per phase, the value k_w is always 1.

Style of Winding	Value of k_w
Two-phase with two slots per pole per phase	.924
Two-phase with three slots per pole per phase	.912
Two-phase with four slots per pole per phase	.908
Three-phase with two slots per pole per phase	.965
Three-phase with three slots per pole per phase	.960
Three-phase with four slots per pole per phase	.958

$\frac{\text{Pole Arc}}{\text{Pole Pitch}}$	Value of k_p
.5	.9
.6	.855
.7	.81
.8	.75

Example.—For the same machine described in the example given in Art. **17**, calculate the demagnetizing ampere-turns according to the more exact method given by the formula in this article, assuming that the ratio $\frac{\text{pole arc}}{\text{pole pitch}} = .6$.

Solution.—The machine has 12 poles and 108 slots, or 9 slots per pole. There are 3 phases; hence, there are 3 slots per pole per phase, and the value of k_w is .96. $k_p = .855$; $T_{pp} = 30$, as in the previous example; and $I_p = 50$. Hence, from the formula,

$$\text{demagnetizing ampere-turns} = .9 \times 3 \times 30 \times 50 \times .96 \times .855 \times .5$$
$$= 1{,}662. \text{ Ans.}$$

The difference between this value and that given by the approximate formula is only 71, or less than 5 per cent.

ARMATURE SELF-INDUCTION

19. Alternator armatures always have more or less **self-induction,** and while this can be measured without difficulty after a machine has been completed, its calculation beforehand is difficult. Many elaborate methods have been proposed for calculating self-induction from the known dimensions of the armature, shape of slots, etc., but all methods are rather uncertain in their results. No attempt will be made here to give formulas for calculating self-induction, but some of its effects and some factors on which it depends are as follows: Self-induction throws the current out of phase with the induced electromotive force, and hence, to a certain extent, is responsible for the demagnetizing effect of the armature on the field. Self-induction also calls for considerable electromotive force to force the current through the armature, thus causing a diminution in the terminal electromotive force.

In general, armatures wound with a few heavy coils embedded in large slots have a high self-induction, because the armature current is able to set up a large number of lines of force around the coils. Machines with this style of armature winding usually give an electromotive-force curve that is more or less peaked and irregular. Such windings are easily applied to the armature and necessitate few crossings of the coils where they project at the ends. They are therefore used largely for high-voltage machines, because they admit of high insulation, while the percentage of slot space occupied by insulation is less than with a machine having a large number of coils.

20. Effect of Subdivided Winding on Induction. The inductance of the coils may be divided into two parts: that due to the portions embedded in the slots, and that due to the end connections. Usually, the slot self-induction is the more important, but in machines with large pole pitch and very narrow armatures, the end connections may be considerably longer than the slot portions, and hence may have equal or greater self-induction.

Fig. 3 (*a*) shows a cross-section of a slot containing a group of conductors forming one side of a heavy coil of twenty-eight turns. When current is passed through the coil, a local magnetic field is set up around the group, as shown by the dotted lines. The self-induced electromotive force, so far as the slot portion of the coil is concerned, depends on the strength of the local field and the number of times it is linked by the coil. The local field depends on the current in the conductors of the coil, the number of turns, and the reluctance of the magnetic path surrounding a side of the coil. If the reluctance remains the same, the self-induced electromotive force for a given current will increase as the square of the number of turns per coil or conductors

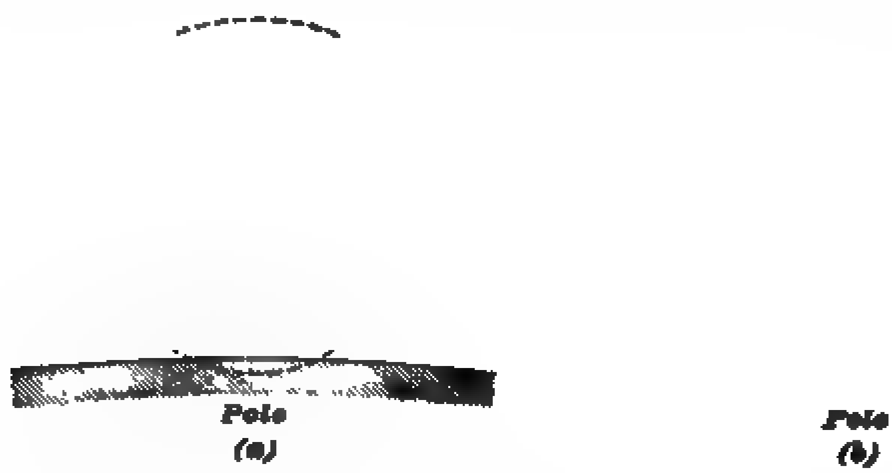


Fig. 3

per slot. Such being the case, the inductance can be decreased by splitting the coil into two or more sections placed in separate slots, thus reducing the number of conductors per slot. For example, an armature with ten twenty-eight-turn coils, each having an inductance of .01 henry, will have a total inductance of $10 \times .01 = .1$ henry. However, if the winding is split up into twenty coils of fourteen turns each, the shape and general arrangement of the coils being kept the same, the reluctance of the local magnetic paths the same, and the total number of turns the same, each coil will have only half as many turns per coil or half as many conductors per slot. Hence, the inductance of each coil will be one-fourth of what it was before, or $\frac{1}{4} \times .01 = .0025$ henry, and the total inductance one-half that in the former case, or $.0025 \times 20 = .05$ henry.

21. In the preceding example, it was assumed that the reluctance of the path around the coil is the same for the heavy coil as for the light one. This, however, is not the case in practice, and the reduction of inductance by subdividing the winding is not so great as the theoretical example just given would indicate. In Fig. 3 (*a*), the greater part of the reluctance occurs at the air gaps around the openings of the slots, as between *a* and *b*, and with a wide, shallow slot, the reluctance between the sides is considerably larger than with a deep, narrow one. When the coils are subdivided, it is necessary to use rather deep, narrow slots, as shown in (*b*), and the reluctance between *a* and *b* is much less than with the wider slot. The result is that the decrease in the number of conductors per slot may be largely offset by the decreased reluctance, so that the product of the flux and the turns may not be reduced nearly so much as the decrease in the number of turns per coil would indicate. With the narrower slots in (*b*), the higher tooth density tends to keep up the reluctance, but saturated teeth are not used so much in alternators as in direct-current machines. Owing to the greater number of coils and the decreased reluctance of the path of the local field flux around the coils, splitting up the winding reduces the total inductance somewhat less than in direct proportion to the reduction in the number of turns per coil; but for machines where low armature inductance and close regulation are desirable, the winding is usually split up in the manner described. Another important reason for distributing the windings is that a wave shape is obtained, approximating a smooth sine wave more nearly than can be obtained with a concentrated winding.

SHORT-CIRCUIT CURRENT

22. Synchronous Impedance.—If an alternator is run at normal speed with its terminals short-circuited, the field excitation necessary to make full-load current circulate in the armature will be only a small part of that required for normal voltage. Under such conditions, the electromotive

force induced in the winding divided by the short-circuit current will give the **synchronous impedance**, that is, the apparent impedance of the armature. The current circulating in the armature, when short-circuited in this way, lags greatly behind the induced electromotive force; its power factor is practically zero and the armature ampere-turns are directly opposed to those on the field. The ampere-turns on the field must overcome the armature back, or demagnetizing, ampere-turns and also set up enough flux to induce an electromotive force sufficient to drive full-load current through the armature against its resistance and self-induction. Since the field required to do this is very small, the

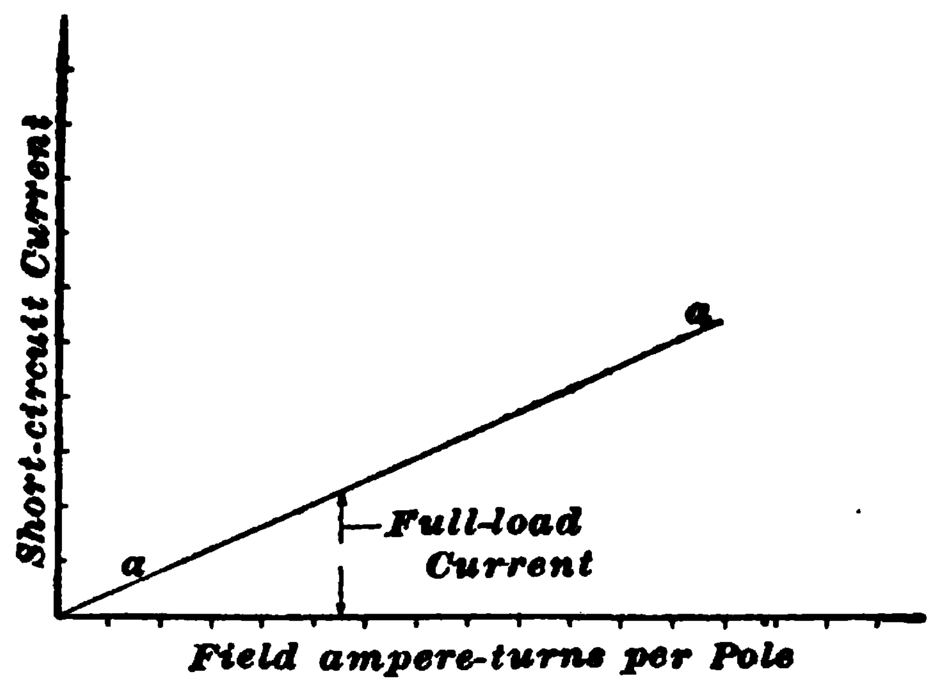


FIG. 4

iron parts are unsaturated; and, within the current limit at which it is safe to operate the machine without overheating, the curve showing the relation between short-circuit current and field ampere-turns is a straight line, as shown at *a a*, Fig. 4. This line is known as the **short-circuit line**, or the **short-circuit current characteristic.**

23. A knowledge of the short-circuit line is useful in calculating the regulation. In most cases, this line can be drawn with a fair degree of accuracy, because numerous tests have shown that for polyphase alternators the ampere-turns per pole on the field bear a definite relation to the ampere-turns per pole on the armature at short circuit. This relation may be expressed as follows:

$$I_f T_f = k_c m I_p T_{pp},$$

in which $I_f T_f$ = ampere-turns per pole on the field;
m = number of phases;
T_{pp} = turns per pole per phase on the armature;
I_p = short-circuit current flowing in each phase when the field has $I_f T_f$ ampere-turns per pole;
k_c = a coefficient depending on the type of machine.

For ordinary two- and three-phase revolving-field alternators, k_c = .85 to .9. Thus, if a value is assumed for the ampere-turns per pole on the field, the corresponding short-circuit armature current can be calculated when m, k_c, and T_{pp} are known. For a given class of machines, the value of k_c is readily determined from tests, and by using the values so obtained for calculating similar machines, the short-circuit line can be drawn, it being necessary to determine only one point in order to fix the direction of the line.

EXAMPLE.—A three-phase alternator has 16 poles and 96 slots, with 6 conductors per slot. What short-circuit current will flow in the armature when the excitation per pole is 800 ampere-turns?

SOLUTION.—There are 96 slots or 6 slots per pole. The number of conductors per pole is 6 × 6 = 36, or 18 turns per pole and 6 turns per pole per phase. Taking k_c = .9, and applying the formula,

$$800 = .9 \times 3 \times I_p \times 6$$

Therefore,

$$I_p = \frac{800}{.9 \times 3 \times 6} = 49.4 \text{ amperes, approximately. Ans.}$$

REGULATION

REGULATION DIAGRAMS

24. The effects of armature reaction and self-induction having been noted, their influence on the regulation and the method by which the regulation can be approximately calculated when a machine is being designed will be more easily understood. To understand clearly the influence of the self-induction and the armature reaction on the voltage at the

alternator terminals, it will be necessary to study the electromotive force diagrams for different kinds of load.

25. Diagram for Non-Inductive Load.—If an alternator is supplying a **non-inductive load**, as, for example, incandescent lamps, the power factor of the load is unity and the current is in phase with the electromotive force at the armature terminals. In Fig. 5, let $O b$ represent the terminal electromotive force and $O a$ the current I in phase with it. The drop in the armature due to resistance is $I R_a = O c$, which is also in phase with the current and

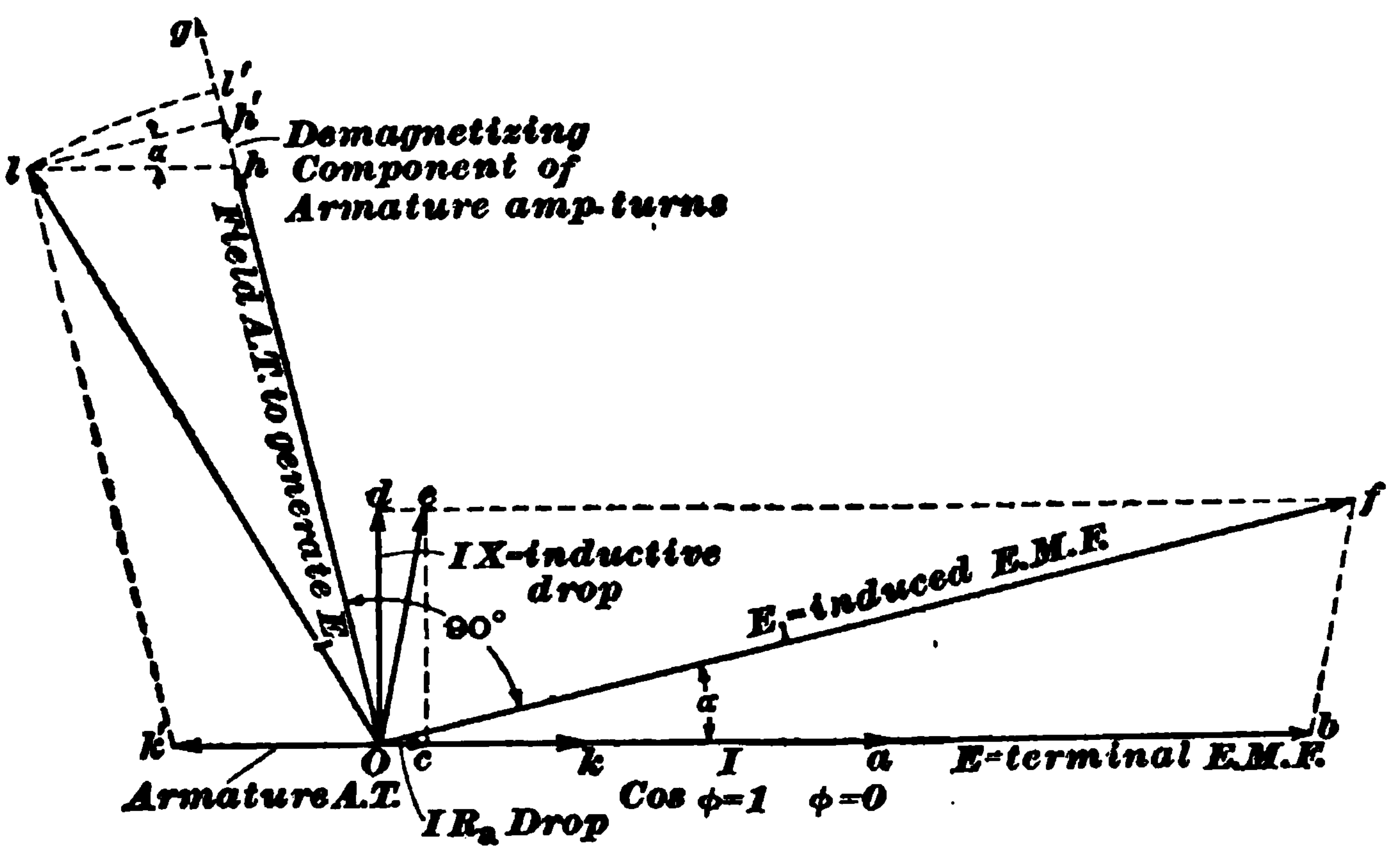


FIG. 5

electromotive force. $O d$ represents the electromotive force required to overcome the self-induction of the armature. Since the electromotive force of self-induction is 90° behind the current, $O d$ is drawn in the opposite direction, or 90° ahead of the current. The resultant of $O c$ and $O d$ is $O e$, representing the electromotive force to overcome the impedance of the armature. The total electromotive force, E_1 induced in the armature is found by completing the parallelogram $O e f b$ and drawing the diagonal $O f$, which represents the resultant of electromotive forces $O e$ and $O b$. Though the load is non-inductive and the current is in phase with the terminal electromotive force, it lags behind the induced

electromotive force E_1 by the angle a, and consequently the armature current exerts a demagnetizing effect on the field.

26. The induced electromotive force in an armature coil is proportional to the rate of change in the number of lines of force passing through the coil, and not to the total magnetism linked by the coil. For example, in Fig. 2 (*a*), the number of lines of force passing through the coil c, c' is, in effect, zero, because an equal number is passing in opposite directions; but as the poles move on, the rate of change in the number of lines is at its greatest; hence, the electromotive force induced in the coil at this instant is maximum. At the position shown in Fig. 2 (*d*), a maximum number of lines is passing through the coil, but the rate of change in this number is least; hence, the electromotive force is minimum. In short, when the resultant field flux through the coil is least, the induced electromotive force is greatest; and when the flux is greatest, the induced electromotive force is least, that is, the field flux is 90° ahead of the induced electromotive force, or in the direction Og, Fig. 5.

The field ampere-turns are proportional to the flux (unless the magnetic circuit becomes saturated), and hence can be laid off along Og to any convenient scale. Let Oh be the field ampere-turns necessary to produce an electromotive force E_1 in the windings when no armature current is flowing. The total ampere-turns required on the field are Oh plus the number required to offset the demagnetizing effect of the armature current. The ampere-turns on the armature will be in phase with the armature current, and can be represented to scale by Ok in phase with Ob. The ampere-turns required to overcome the armature reaction will be Ok', equal and opposite to Ok. The total ampere-turns required on the field to induce the electromotive force E_1 and to overcome the armature reaction Ok will be Ol, which is found by completing the parallelogram $Ohlk'$. The component of the armature reaction parallel with the field is hh', found by drawing lh' perpendicular to Og; $lh = Ok'$ = armature ampere-turns, and angle $h'lh = bOf = a$. The demagnetizing

component of the armature ampere-turns is therefore

$$h\,h' = l\,h \sin a = \text{armature ampere-turns} \times \sin a,$$

in which a is the angle by which the current and the terminal electromotive force lags behind the induced electromotive force.

27. The excitation $O\,h$ alone is not sufficient to obtain an induced electromotive force E_1 when the armature current is flowing, but if the field ampere-turns are increased to $O\,l' = O\,l$, the added excitation will be more than sufficient to overcome the demagnetizing component $h\,h'$.

If the excitation is adjusted to give E volts and the load is then thrown off, the voltage at the terminals will at once

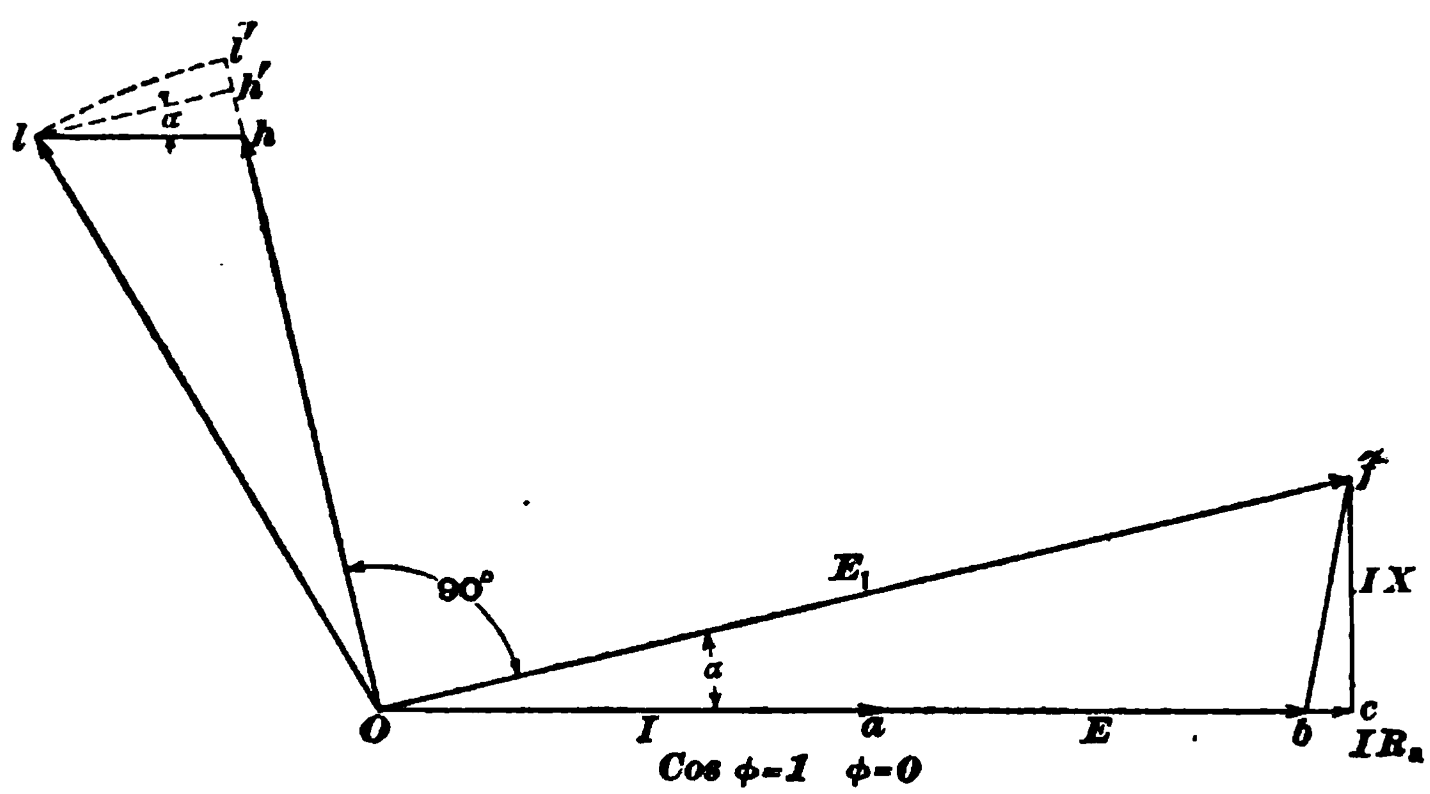


FIG. 6

rise to that corresponding to an excitation $O\,l$, with the armature on open circuit.

Fig. 6 is the same as Fig. 5, except that a number of the lines have been omitted and triangles used instead of parallelograms in order to simplify the figure. The armature-drop triangle has been transferred to b, but the lengths of the various lines in the two figures are the same.

28. Diagram for Inductive Load, With Power Factor of .8.—In Fig. 7, the diagram is for an **inductive load** with a power factor of .8; the load might easily have as low a power factor as this when induction motors are

operated. The current Oa is of the same value as in Fig. 6, but now lags 36° 50′ (cos 36° 50′ = .8) behind the terminal electromotive force E, which also has the same value as in Fig. 6. The resistance drop is always in phase with the current; therefore, bc, Fig. 7, must be drawn parallel with Oa, while cf, representing the electromotive force to overcome the drop due to the inductance of the armature, is at right angles to the current and hence to bc. The triangle bfc is therefore swung around to the position shown, and the total

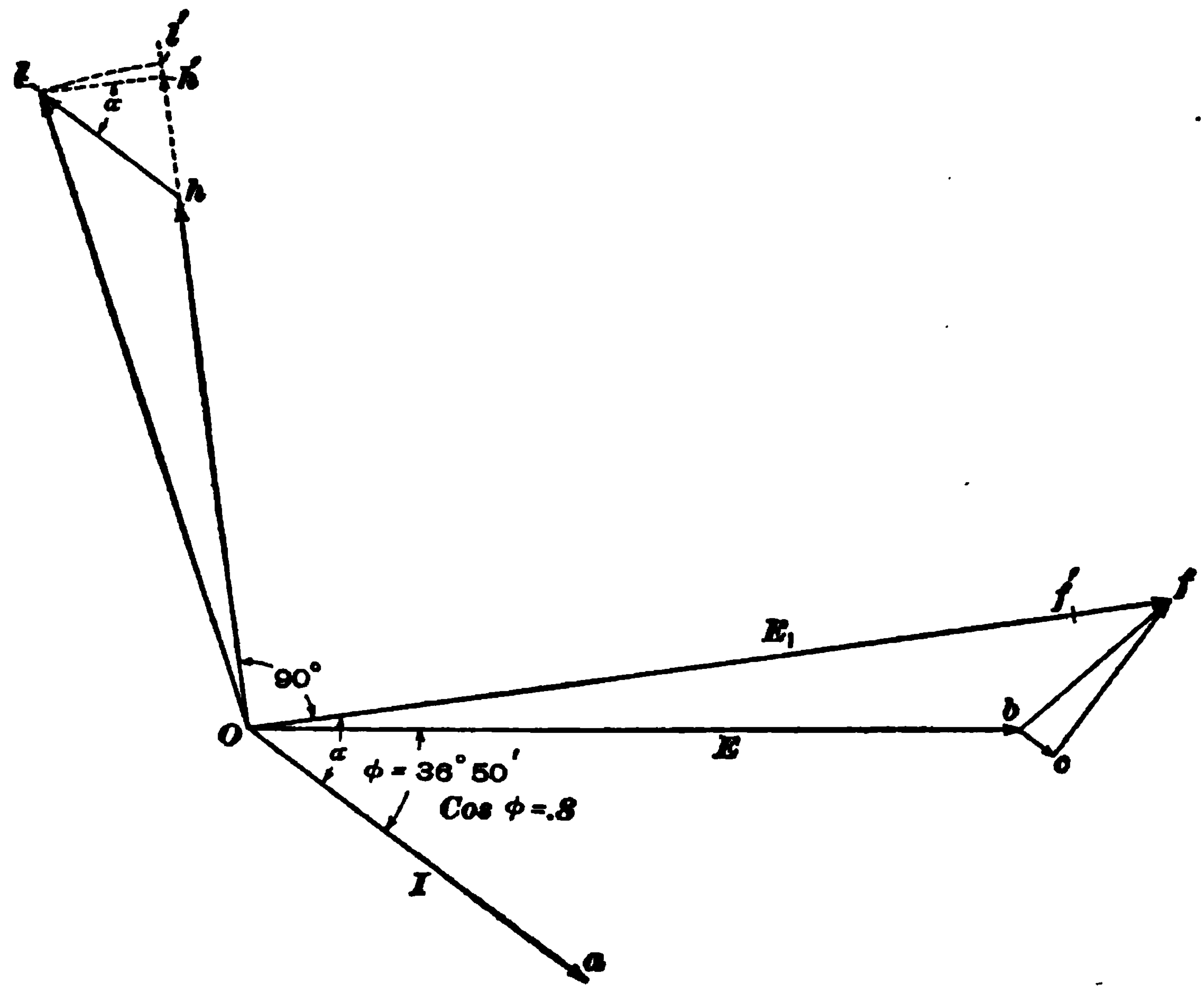


FIG. 7

induced electromotive force is represented in value and in phase relation by E_1. Of' is equal to Of, Fig. 6; that is, reducing the power factor from 1 to .8 necessitates increasing the induced electromotive force by an amount represented by $f'f$, Fig. 7, in order to maintain the same terminal voltage represented by the line E. Moreover, the armature ampere-turns, being in phase with the current, may be represented by a line hl parallel with Oa. The demagnetizing component hh' is much larger than with the non-inductive load,

and the field excitation is therefore increased to $O\,l' = O\,l$; if the load is thrown off, the electromotive force obtained at the terminals rises to that corresponding to an excitation $O\,l$ with the armature on open circuit.

29. Diagram for Load of Low Power Factor. When the power factor becomes very low, the diagram

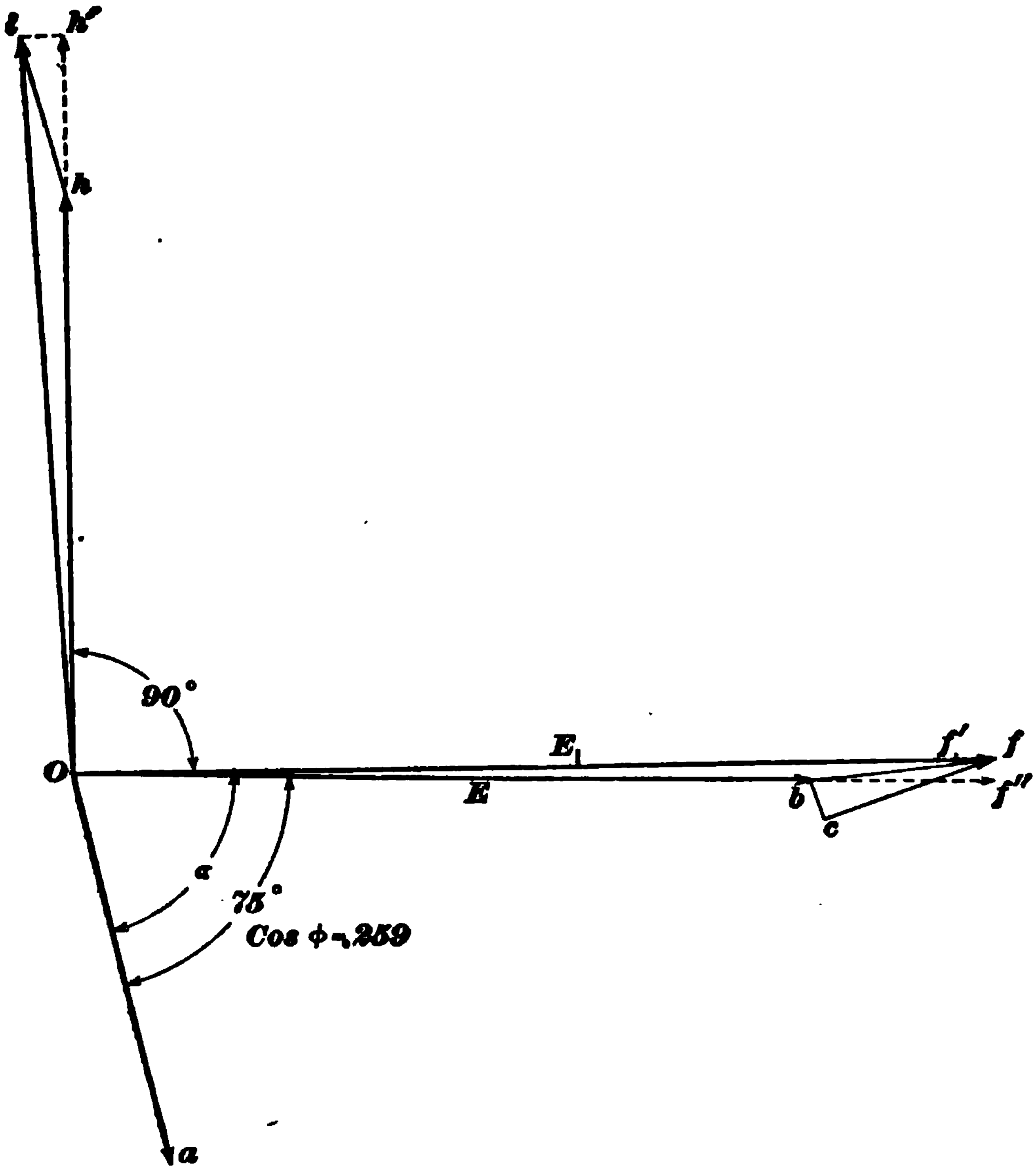


FIG. 8

takes the form shown in Fig. 8, which is drawn for an angle of lag of 75° or a load power factor of .259. E_1 is the induced electromotive force, and $O\,f'$ is equal to $O\,f$, Fig. 7, so that the decrease in power factor from .8 to .259 has necessitated an increase in E_1 only by the amount $f'\,f$, Fig. 8, for the same terminal electromotive force E. The decrease from power factor 1 to power factor .8 made the difference

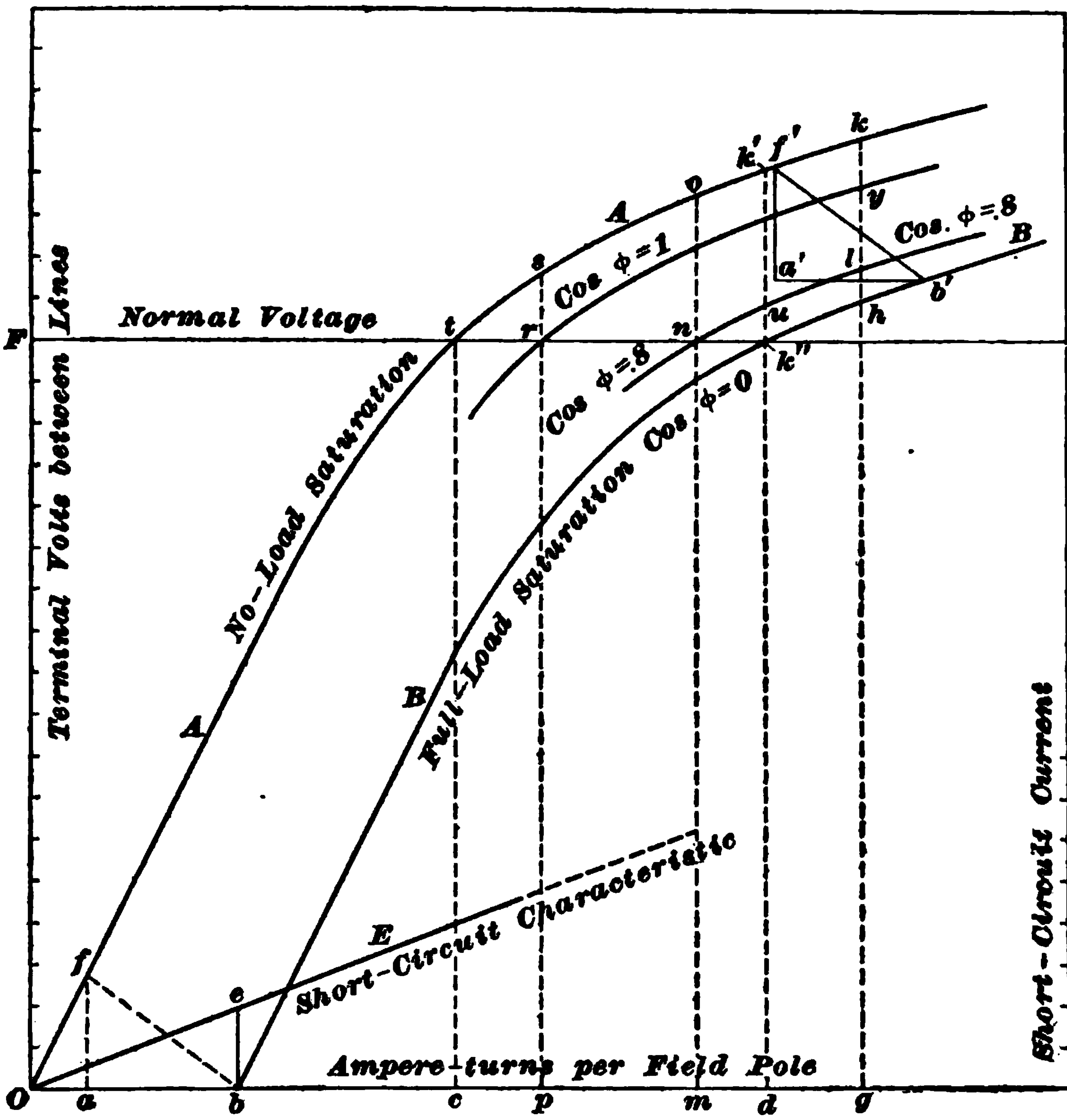
$f' f$ in Fig. 7. When the power factor becomes low, say below .25, a further reduction makes very little difference in the induced electromotive force required to maintain a given terminal electromotive force E. Moreover, with a very low power factor, the armature ampere-turns $h\,l$, Fig. 8, and the impedance drop $b\,f$ in the armature become so nearly in line with $O\,h$ and $O\,f$, respectively, that they can be added or subtracted arithmetically without drawing triangles, that is, making $h\,h' = h\,l$ and $b\,f'' = b\,f$; $O\,h'$ is then almost exactly equal to $O\,l$, and $O\,f'$ to $O\,f$. Because of this, the most convenient load for which to estimate the regulation is that having a very low power factor or approximately a zero power factor. After the regulation for this load has been determined, the approximate regulation for loads of other power factors may be estimated, as will be explained.

SATURATION CURVES

30. In Fig. 9, let the curve $O\,A\,A$ represent the **no-load saturation curve** of an alternator. This curve is similar to the saturation curve of a direct-current machine and shows the relation between field excitation and voltage at the machine terminals when run on open circuit; it is calculated the same as for direct-current generators, its lower part being a straight line. After parts of the magnetic circuit become saturated or partially so, the curve bends off to the right. Distances along the horizontal are usually laid off either in ampere-turns per pole or in exciting current.

31. The short-circuited current characteristic $O\,E$ can also be drawn by calculating the ampere-turns $O\,b$ necessary to force any given current, say full-load current $b\,e$, through the armature when short-circuited. The full-load current is known; hence, $O\,b$ can be determined approximately by the formula of Art. **23**. When full-load short-circuit current is circulated in the armature, the power factor is very low; and if the short-circuiting connections have zero impedance, the electromotive force at the terminals is zero. In order to determine the regulation for a load of zero power factor, a curve

similar to $A A$ must be drawn, showing the relation between the field excitation and the voltage between the machine terminals when constant full-load current is flowing through the armature. To keep the current constant the alternator can be connected to a load of very low power factor and the load changed as the field excitation is increased.



ab=*Armature Demagnetizing Ampere-turns Cos. φ=0*
be=*Full-Load Short-Circuit Current*

FIG. 9

32. When the terminal electromotive force is zero, an excitation $O b$, Fig. 9, is required to force the current through the armature; hence, the full-load saturation curve for any load power factor must begin at point b. It was explained in Art. **29** that for zero power factor the armature demagnetizing

ampere-turns could be subtracted directly from the field ampere-turns, and that the inductive drop could be subtracted directly from the induced electromotive force. With zero terminal electromotive force, $O\,b$ ampere-turns are required, and of these $a\,b$ represents the armature demagnetizing ampere-turns, as found by formula **2**, Art. **17**, or more nearly correct by the formula of Art. **18**. The demagnetizing ampere-turns are subtracted from $O\,b$, leaving $O\,a$ as the actual number of ampere-turns effective in inducing electromotive force in the armature. On open circuit, the ampere-turns $O\,a$ would produce an electromotive force $a\,f$, f being the point on the no-load saturation curve corresponding to $O\,a$ ampere-turns. If the armature current is kept constant, the armature drop $a\,f$ and the armature reaction $a\,b$ can be considered constant; hence, the load saturation curve $B\,B$ for zero power factor can be drawn. For example, from any point f' on curve $A\,A$ subtract $f'\,a' = f\,a$. So far as the armature drop is concerned, an excitation corresponding to point f' on the open-circuit curve would give a voltage represented by point a' when the machine delivered full load at zero power factor. The excitation, however, must be increased by $a'\,b' = a\,b$ in order to offset armature reaction; hence, b' is a point on the full-load saturation curve. By moving the triangle $f'\,a'\,b'$, keeping point f' on the curve $A\,A$ and moving the triangle parallel with itself, curve $B\,B$ can be traced; that is, the full-load saturation curve for zero power factor is found from the no-load curve by shifting the no-load curve downwards a distance representing the armature drop, and to the right a distance representing the armature reaction.

33. Line $F\,F$, Fig. 9, represents the normal voltage; hence, with a load of zero power factor, a field excitation $O\,d$ must be applied to maintain normal voltage. If, with this field excitation, the load is thrown off, the voltage will at once rise to $d\,k'$, and $k''\,k'$ is the increase in terminal pressure. On open circuit, an excitation $O\,c$ is sufficient to obtain normal voltage, and throwing on full-load current at zero

power factor necessitates an increase *c d* in the excitation in order to maintain the voltage. If the fields were not designed to admit of this increase with the available exciter voltage, the terminal voltage could not be maintained at zero power factor. Although operation at zero power factor is seldom required, an alternator designed so that the voltage can be maintained under such conditions will be easy to regulate on loads of higher power factor; there will be no difficulty in

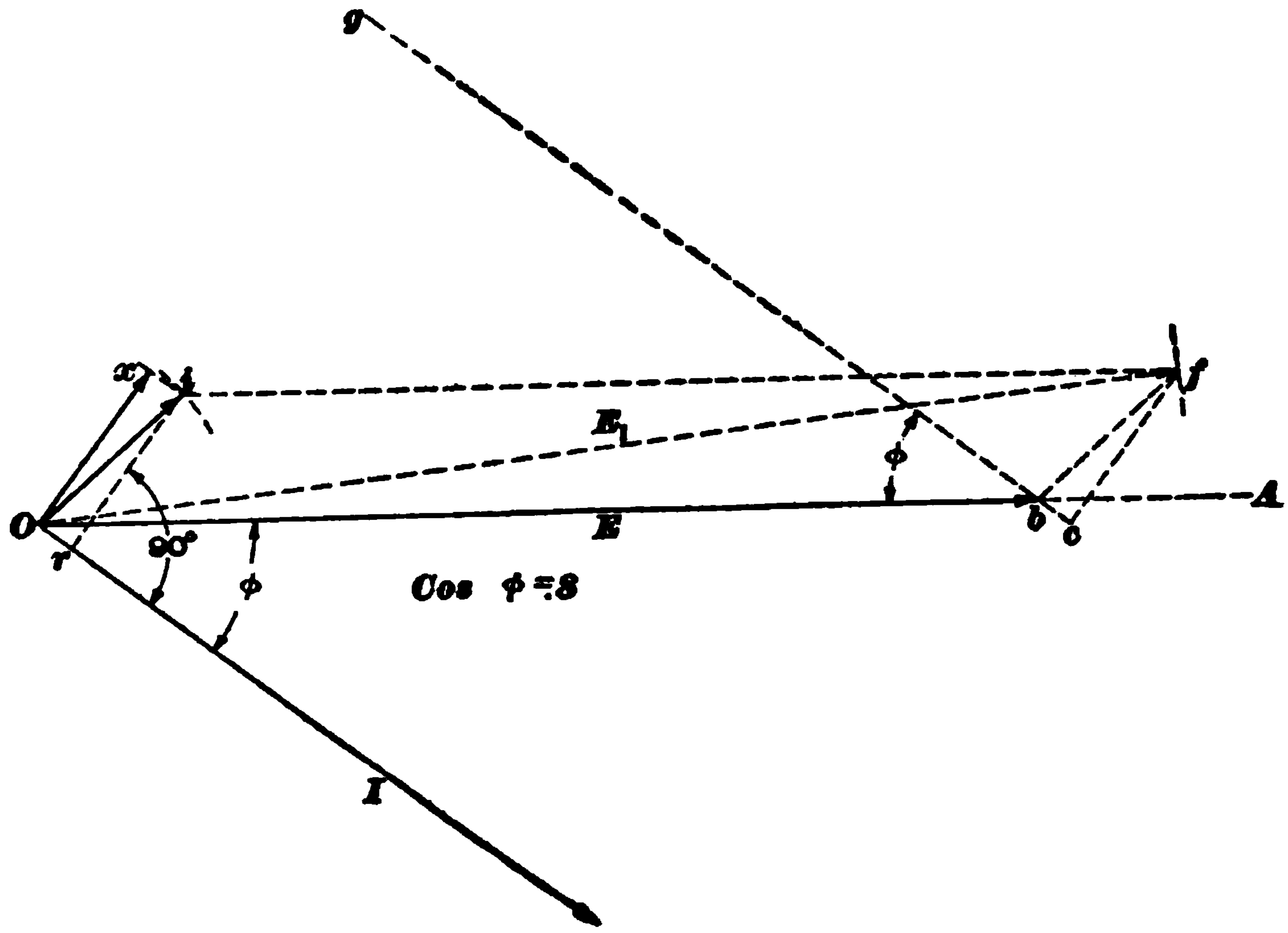


FIG. 10

exciting the fields to maintain the voltage on loads of any power factor.

34. Determination of Regulation on Load of Given Power Factor.—After the curve *B B*, Fig. 9, for zero power factor has been drawn, the curve *n l* may be constructed for any power factor, say, .8. Points on the curve *n l* may be found as follows: Assume any convenient excitation—for example, that corresponding to an open-circuit voltage *g k* and a full-load voltage on zero power factor *g h*—then, *h k* is the total voltage drop when the load is thrown on.

Referring to Fig. 10, let *O A* represent the direction of the terminal electromotive force at power factor .8, the value of

which is to be found. OI represents the direction of the current, the angle ϕ being such that $\cos \phi = .8$. The electromotive force Oi ($= hk$, Fig. 9) required to overcome the synchronous impedance is the resultant of the known resistance drop Or parallel with OI, Fig. 10, and the unknown reactance drop Ox at right angles to OI; hence, by laying off Or equal to the resistance drop and drawing a line perpendicular to OI, the point i can be found by striking an arc from O as a center with a radius Oi. The reactance drop represented by $Ox = ri$. The total induced electromotive force is equal to gk, Fig. 9, because with the excitation Og the voltage rises to gk when the load is thrown off. This total electromotive force is the resultant of that lost in the armature Oi, Fig. 10, and the unknown terminal electromotive force E; hence, drawing a line from i parallel with OA, intersecting this line at f with an arc drawn from O as a center and with a radius E_1 equal to gk, Fig. 9, and drawing fb, Fig. 10, parallel with Oi, the point b is located, thus determining the value of the terminal electromotive force E on power factor .8, as Ob. Laying off gl, Fig. 9, equal to Ob, Fig. 10, one point l on the curve for power factor .8 is located. With field excitation Og, the electromotive force at no load will be gk, and with full-load current at power factor .8, it will be gl.

35. In order to determine a number of points on the curve for power factor .8, it is not necessary to construct a complete figure similar to Fig. 10 each time. The points can be obtained more quickly in the following manner: Draw a horizontal line pbc, Fig. 11, and make bc equal to the resistance drop in the armature. At c erect a perpendicular of indefinite length, and from b draw a line bO at an angle ϕ so that its cosine is equal to the power factor under consideration, in this case, .8. With b as center and a radius equal to the total armature drop hk, Fig. 9, strike an arc cutting the vertical at f, Fig. 11. Then, with f as center and a radius equal to the open-circuit electromotive force gk, Fig. 9, strike an arc cutting the line bO, Fig. 11, at O; bO is then the terminal

electromotive force. The polygons of electromotive forces $O\,f\,c\,b\,O$ are exactly the same in both Figs. 10 and 11; this will be more evident if the dotted line $c\,g$ parallel with $O\,I$, Fig. 10, is taken as the direction of the current and the whole figure conceived to be swung around until line $c\,g$ is horizontal.

36. To obtain another point on the curve for power factor .8, say that corresponding to excitation $O\,d$, Fig. 9, strike an arc from b, Fig. 11, as a center and with a radius equal to $k'\,k''$, Fig. 9, thus giving point f', Fig. 11. Then,

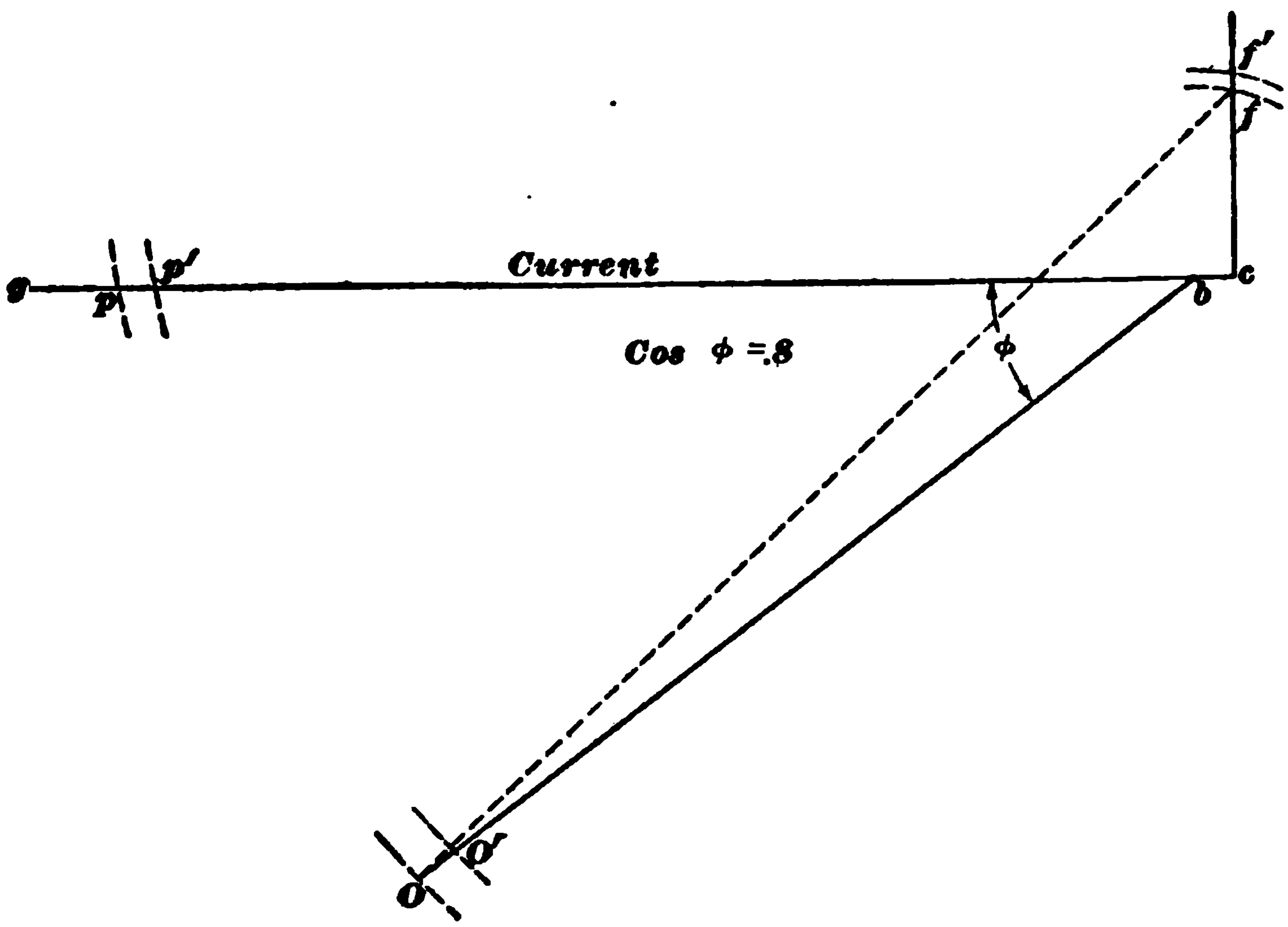


Fig. 11

with f' as center and with a radius $d\,k'$, Fig. 9, strike an arc, cutting the line from b, Fig. 11, at O'; make $b\,O' = d\,u$ in Fig. 9, thus locating a second point u on the curve. In the same way, other points may be found and the whole curve drawn in. Only part of the curve is shown in Fig. 9, as it is seldom necessary to draw the whole of it. If continued downwards, the curve would terminate in point b on the horizontal.

37. For the curve corresponding to power factor unity, that is, non-inductive load, the angle ϕ, Fig. 11, becomes zero, and the intercepts, such as p, p', on the horizontal determine the values of two terminal electromotive forces, the arcs

being struck from centers located, as before, on the perpendicular through c. The curve for unity power factor and full-load current will be as shown at ry, Fig. 9; this curve would also terminate in point b if plotted all the way down.

38. Having obtained these curves, the regulation may be estimated. Line FF, Fig. 9, represents normal voltage, and with full load at power factor unity, a field excitation Op is required to maintain normal voltage. When the load is thrown off, the voltage rises to ps; hence, the regulation is $\frac{rs}{pr}$, or $\frac{rs}{pr} \times 100$ if it is to be expressed as a percentage. With power factor of .8, the regulation is $\frac{on}{mn}$, and the variation in voltage when the load is thrown off is very much greater than on a non-inductive load. With zero power factor, the regulation is $\frac{k' k''}{d k''}$. The curves plainly show the great influence the character of the load has on the regulation, and why it is necessary to state the power factor of the load in every case where regulation is specified.

39. The foregoing method of estimating regulation is not exactly correct, because it is difficult to separate the effects of armature reaction and self-induction; also, there are a number of points that are not taken into account in the method. For example, when the armature is delivering current, the field ampere-turns must be increased in order to keep up the voltage, and this increases the magnetic leakage between poles; whereas, in Fig. 9, the open-circuit saturation curve is used in determining the regulation, and the leakage is therefore taken as the same, whether the machine is delivering current or not. Again, there is liable to be more or less inaccuracy in the calculations of the short-circuit line. It is possible to make corrections that add to the accuracy of the calculations, but the foregoing method illustrates the principles involved, and is therefore very useful in forming an approximate estimate of the behavior of a machine when operating on loads of various power factors.

FIELD LEAKAGE

40. The ability of an alternator to hold up its voltage on loads of low power factor depends very largely on the **field leakage.** The greater part of the flux set up through the poles passes through the armature core and is useful in generating an electromotive force; but some lines of force leak across the space between the poles without entering the armature core, and this leakage flux produces no electromotive force. The *field-leakage coefficient* is the ratio

$$\frac{\text{total flux}}{\text{useful flux}} = \frac{\text{useful flux} + \text{leakage flux}}{\text{useful flux}}.$$

In ordinary alternators, the value of the leakage coefficient usually lies between 1.1 and 1.5.

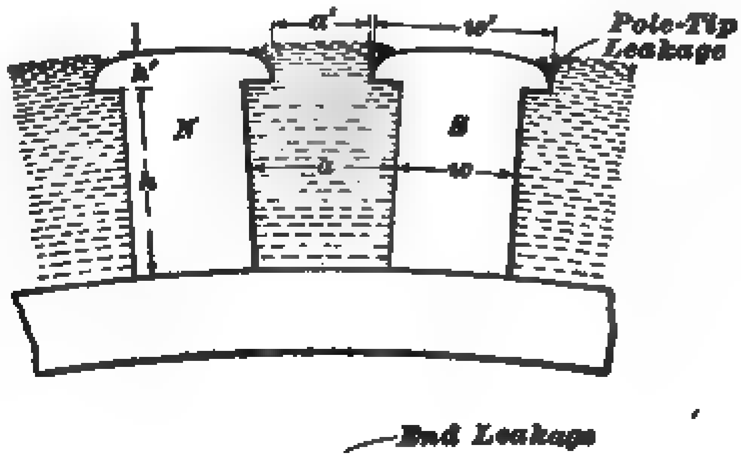


FIG. 12

41. Calculation of Leakage Flux.—In Fig. 12, N and S represent two adjacent poles of a revolving field, and the dotted lines represent the **leakage flux** between poles.

For convenience, the flux may be divided into four parts as follows: (1) Leakage between the pole-core sides of height h and length L; (2) leakage between pole tips of height h' and length L; (3) end leakage between ends of pole cores of height h and width w; and (4) end leakage between ends of pole shoes of height h' and width w'.

The density of the leakage flux is greatest at the upper part of the poles and between the pole shoes, because at these places all the ampere-turns are effective, and also because the leakage path between the pole shoes is shorter than elsewhere; the flux density decreases as the yoke is approached. Since the leakage paths are in parallel with the path of the useful flux, the ampere-turns effective in setting up leakage are the same as those necessary to force the flux through the air gap, armature core, and teeth; for all practical purposes, these ampere-turns may be taken as the same as the ampere-turns for the air gap, since the number required for the core and teeth is very small.

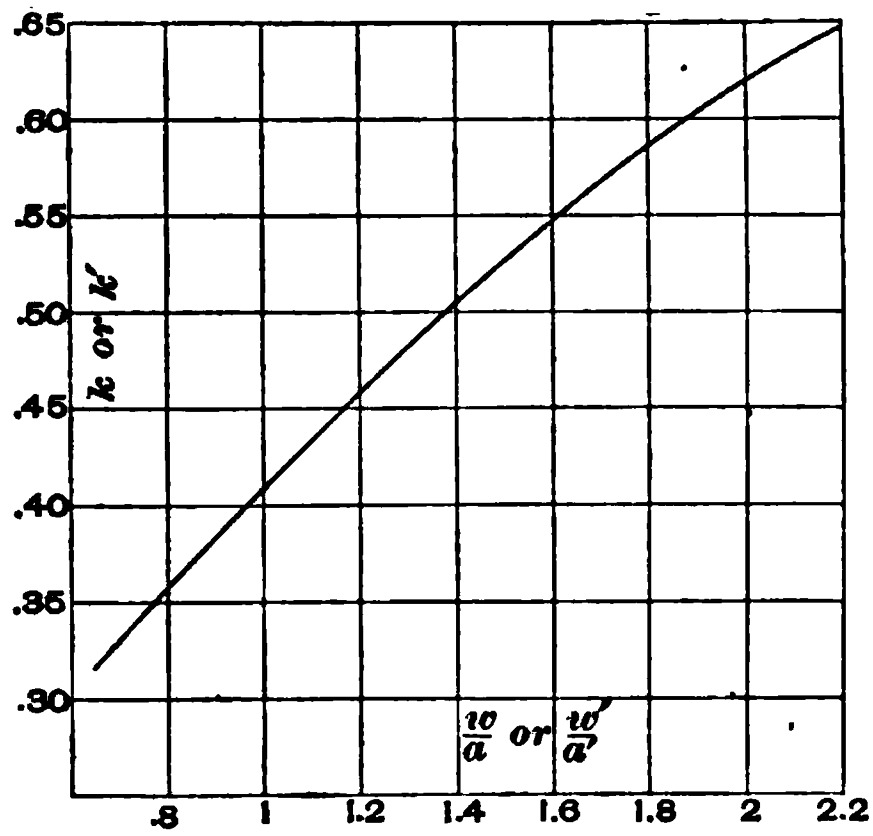


FIG. 13

If X represents the number of ampere-turns per pole required for the air gap and the dimensions, in inches, of the poles are as indicated by the letters in Fig. 12, the leakage flux per pole Φ_l can be calculated approximately by the following formula:

$$\Phi_l = 3.19X\left[\left(\frac{4h'}{a'} + \frac{2h}{a}\right)L + 3.2\,h\,k + 6.42\,h'\,k'\right],$$

in which k and k' are coefficients depending for their values on the ratios $\frac{w}{a}$ and $\frac{w'}{a'}$, respectively. For known values of $\frac{w}{a}$ or $\frac{w'}{a'}$, the values of k and k' can be obtained from the curve given in Fig. 13.

EXAMPLE.—An alternator has poles of the following dimensions, in inches: $h' = .5$; $h = 6$; $w = 3$; $w' = 5$; $a = 4$; $a' = 2.4$; and $L = 8$. The ampere-turns per pole for the air gap is 3,000, and the useful flux per pole is 2,500,000 lines. (*a*) Calculate the leakage flux Φ_l. (*b*) What is the leakage coefficient of the field?

SOLUTION.—(*a*) First find the values of k and k' from Fig. 13. $\frac{w}{a} = \frac{3}{4} = .75$; hence, $k = .342$. $\frac{w'}{a'} = \frac{5}{2.4} = 2.08$ and $k' = .63$. Substituting the other values in the formula,

$$\Phi_l = 3.19 \times 3{,}000\left[\left(\frac{4 \times .5}{2.4} + \frac{2 \times 6}{4}\right)8 + 3.2 \times 6 \times .342 + 6.42 \times .5 \times .63\right]$$
$$= 3.19 \times 3{,}000\,[30.6 + 6.6 + 2]$$
$$= 3.19 \times 3{,}000 \times 39.2 = 375{,}144 \text{ lines, approximately. Ans.}$$

(*b*) The useful flux is 2,500,000 lines, and the total flux is 2,500,000 + 375,144 = 2,875,144 lines; hence,

$$\text{leakage coefficient} = \frac{2{,}875{,}144}{2{,}500{,}000} = 1.15. \text{ Ans.}$$

As indicated in the formula, the leakage flux is the sum of the products of the magnetomotive force $3.19\,X$ and four separate terms as follows: $\frac{4\,h'}{a'} \times L$; $\frac{2\,h}{a} \times L$; $3.2\,h\,k$; and $6.42\,h'\,k'$. The first of these gives the leakage flux between the pole tips facing each other; the second, the flux between the pole sides; the third, the leakage between the ends of the pole cores; and the fourth, that between the ends of the pole shoes.

42. In order to avoid excessive field leakage, the distances a' and a, Fig. 12, must be made as large as practicable; this means that the pole pitch, or distance between centers of poles, must be liberal. Machines built with small diameters and having crowded field poles invariably have large magnetic leakage. Again, the length L, should not be too great, and as a general rule should not exceed two and one-half times the pole pitch. In other words, machines of large diameter and with fairly short poles, measured parallel with the shaft and with liberal space between the poles, have much less leakage than those of smaller diameter with longer poles crowded closely together.

RELATION BETWEEN FIELD AND ARMATURE AMPERE-TURNS

43. Since the armature exerts a powerful demagnetizing action on the field, particularly when the load is inductive, the field must be powerful as compared with the armature, otherwise variations in the armature current will produce great changes in the field flux and lead to very poor regulation. In modern alternators, the ampere-turns per pole on the field required for the air gap will usually be from two to two and one-half times the ampere-turns per pole on the armature in 60-cycle machines, and from one and one-fourth to two times in 25-cycle machines. The allowable magnetic density in the air gap is limited and cannot be pushed beyond the limit without making the density in the teeth too high. If l_g is the length of the single air gap, in inches, and B_g the allowable gap density, in lines per square inch, then the ampere-turns per pole on the field required for setting up the flux through the air gap is

$$I\,T_g = .313\,B_g\,l_g \qquad (1)$$

As just explained, the field ampere-turns $I\,T_g$ are fixed, to a certain extent, by the armature ampere-turns, and B_g is also limited; hence, the air gap must be made of such a length that

$$l_g = \frac{I\,T_g}{.313\,B_g} \qquad (2)$$

This length of gap may be very much greater than required for mechanical clearance between stator and rotor. For example, in large alternators for direct connection to steam turbines, the speed is so high that the number of poles is very small, perhaps only two or four. The number of ampere-turns per pole on the armature is very great, while the number on the field must be still greater. To secure the proper density in the air gap, the gap must be long, the clearance between field and armature in some large machines being 1½ or 2 inches. In ordinary alternators with numerous poles, the ampere-turns per pole on the armature are less; also, a smaller air gap can be used, though in most cases it is larger than is necessary for mechanical clearance.

SUMMARY OF REQUIREMENTS FOR GOOD REGULATION

44. The following is a summary of the main points that should be observed in order to obtain good regulation:

1. Make the armature of sufficiently large diameter, so that the poles will not be crowded together and cause excessive magnetic leakage.

2. Design the armature to have as low self-induction as practicable, thus keeping down the inductive drop and also decreasing the angle of lag between the current and the induced electromotive force. The slots should neither be too deep nor too narrow, and the winding should be subdivided if possible.

3. Make the field magnetically strong as compared with the armature; that is, make the air gap of such length that the ampere-turns per pole on the field necessary to set up the required air-gap density, will be much greater than the armature ampere-turns per pole.

4. Partially saturate the magnetic circuit, so that the machine will be worked well up on the bend of the saturation curve. Considerable variation in the effective ampere-turns per pole will not then affect the flux and voltage so much as if the magnetic circuit were unsaturated.

MAGNETIC DENSITIES

45. On account of the high frequency, the **magnetic density** in the armature teeth and core must be kept somewhat lower than in direct-current machines, the allowable density limit depending to some extent on the frequency of the alternator. For example, in a 25-cycle machine, the densities can be higher than in a 60-cycle machine.

46. Air-Gap Density.—In 60-cycle alternators, the **air-gap density** is usually from 40,000 to 50,000 lines per square inch, 45,000 being a fair average. Unless the teeth are unusually large, this density cannot be forced much higher without making the tooth density too high. With subdivided

windings, the teeth are frequently very little wider than the slots, so that the tooth density is approximately twice that in the air gap. With very large teeth, the density might be run somewhat higher, but as a general rule 50,000 is about the limiting value for 60-cycle machines. For 25-cycle alternators, the density may be run up to 55,000 or even 60,000 when the teeth are of large cross-section.

47. Density in Teeth.—The maximum **tooth density** should not exceed from 90,000 to 110,000. With bunched windings having comparatively few slots and large teeth, the density can usually be kept near the lower limit or even less; but with subdivided windings with a large number of slots, the cross-sectional area of the teeth is necessarily smaller and a higher density is unavoidable. However, the volume of the small teeth is less, so that even with a higher density the total loss may be but little more than with the large teeth worked at a low density.

48. Density in Armature Core.—The **density in the armature core** under the slots must be kept rather low, because the volume of iron is comparatively large; and if a low density is not used, the core loss will be too great. From 30,000 to 35,000 are fair values for 60-cycle machines, while for 25-cycle alternators, the density may be run up to 45,000 or 50,000.

49. Density in Field Cores.—The field poles are usually made either of laminated-steel punchings or of cast steel, and the density in the pole cores is usually from 80,000 to 100,000. It is economical to use a rather high density in the cores, because the field flux is not alternating and there is no hysteresis. Moreover, by running up the density in the pole cores, their cross-section can be made smaller and their periphery less, making the mean length of field turn shorter and thus reducing the amount of copper required for winding the field coils.

50. Density in Spider Rim.—The cross-section of the **spider rim** for revolving fields is determined more by

mechanical than by magnetic considerations. A cast-iron rim should have at least cross-section enough to limit the density to 35,000 or 40,000, while in a cast-steel rim the density can be as high as 60,000 to 65,000. However, the densities are frequently lower than these values, since the rim is made with a view of providing ample mechanical strength. This is specially so in alternators of large diameter having many small poles and correspondingly small flux per pole. The spider rim for such machines, if designed merely to carry the magnetic flux, would be entirely too light for mechanical strength.

CALCULATION OF AIR-GAP AMPERE-TURNS

51. In an alternator, the armature teeth are usually rather coarse and the slots wide, so that the magnetic flux from the pole is in *tufts*, somewhat as shown in Fig. 14.

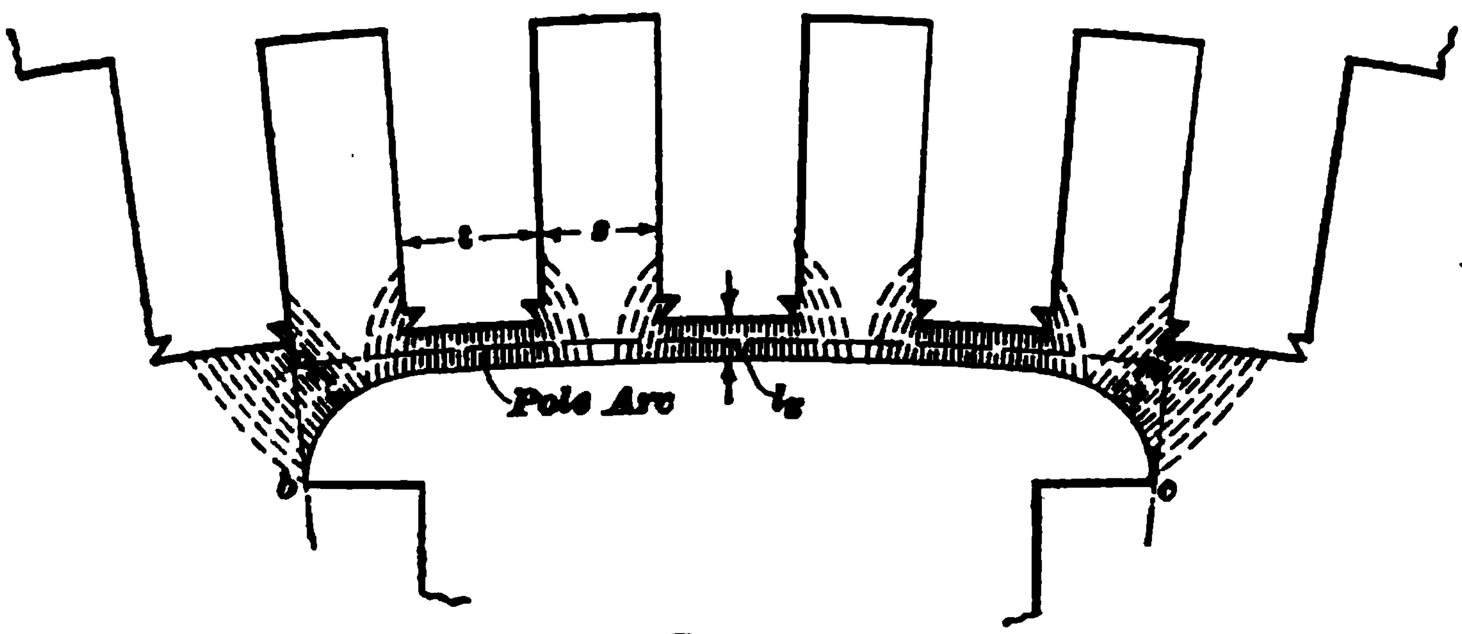


FIG. 14

The actual density in the gap is greater than the value obtained by dividing the total flux per pole by the area of the pole face, and the actual ampere-turns required for the air gap are therefore greater than those obtained from calculation based on the assumption that the lines are uniformly distributed. To allow for this bunching of the lines, the ampere-turns can be calculated for an air gap slightly longer than the actual gap l_g, the increased length depending on the dimensions of the slots and teeth and the length of the gap.

Also, as shown in Fig. 14, the effective polar arc is larger than the actual arc measured between dotted lines bc, owing

to the fringing of the flux at the pole tips. To obtain the effective polar arc, it is therefore necessary to add a certain amount to the actual arc, and this corrected length of polar arc multiplied by the length of the pole parallel with the shaft gives the effective area of the pole face. The total flux divided by the effective pole area, in square inches, gives the average air-gap density B_g in lines per square inch, and formula **1**, Art. **43**, can be written

$$I\,T_g = .313\,B_g\,l'_g,$$

where l'_g is the corrected length, in inches, of the single air gap.

52. Corrections for Pole and Tooth Fringing.—The following formulas and curves, which give corrections for pole and tooth fringing, work very well in calculating the

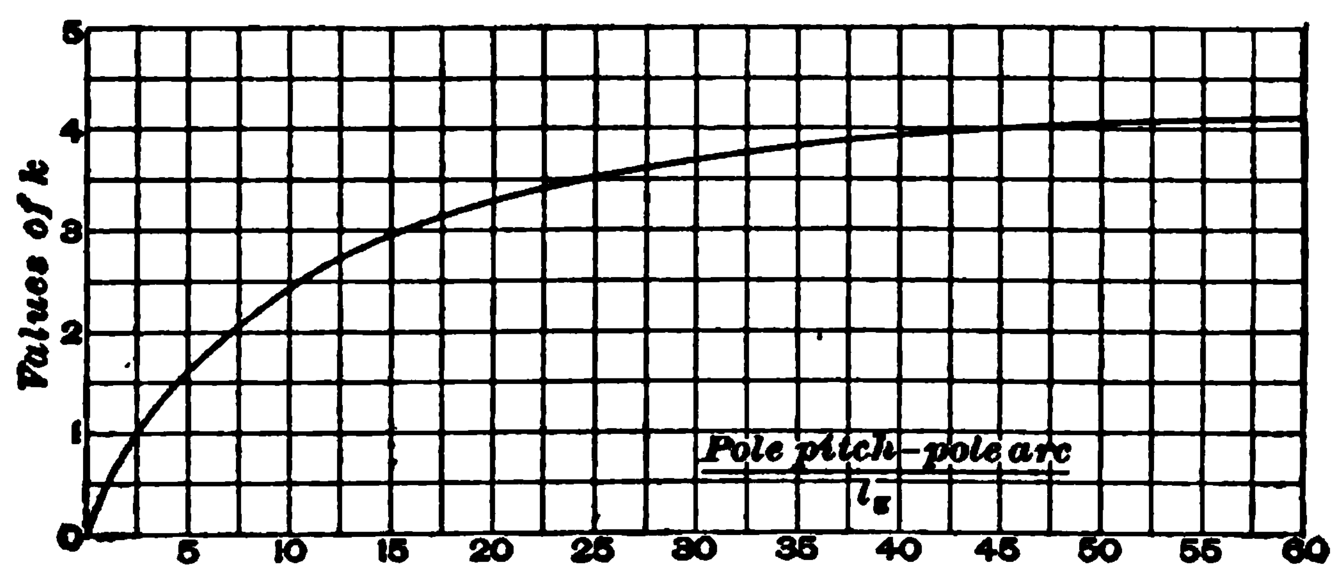


FIG. 15

air-gap ampere-turns for ordinary revolving-field alternators. The effective polar arc is obtained by the following formula:

$$\text{effective arc} = \text{actual arc} + k\,l_g,$$

in which k is a coefficient depending on the ratio

$$\frac{\text{pole pitch} - \text{pole arc}}{l_g}$$

(see Fig. 15), and l_g the single air gap, in inches.

53. The effective air gap l'_g is found by the following formula:

$$l'_g = \left(\frac{1 + \frac{s}{t}}{1 + k'\frac{s}{t}}\right) l_g,$$

in which l_g = actual air gap;

s = width of slot opening at air gap;

t = width of tooth at air gap;

k' = coefficient depending on the ratio $\frac{s}{l_g}$.

In this formula, s is always the slot opening at the air gap, and with partly closed slots would be less than the width of the slot proper. The values of k' for various values of the ratio $\frac{s}{l_g}$ are given by the curve in Fig. 16.

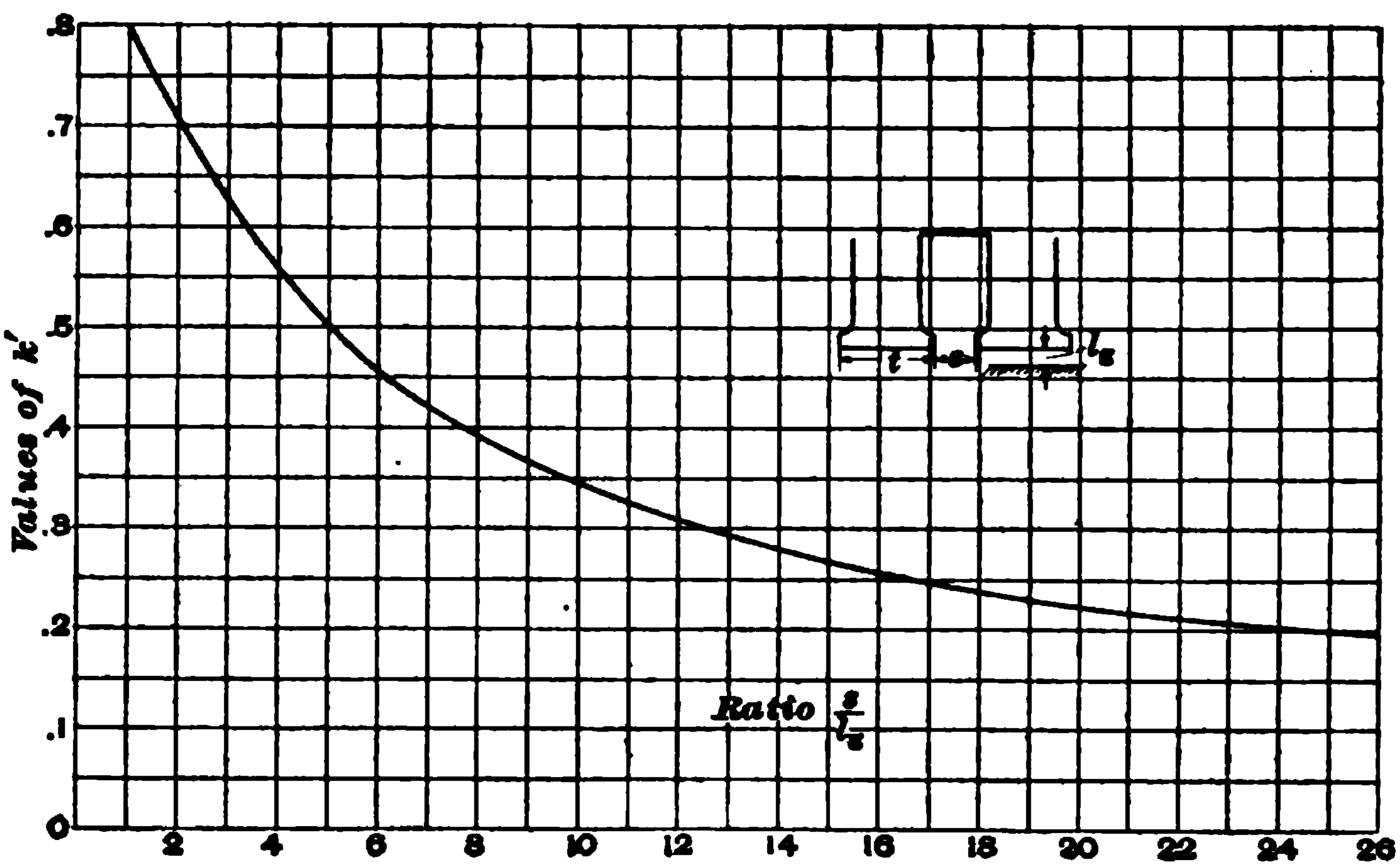


FIG. 16

EXAMPLE.—The pole pitch of an alternator is 8 inches, and the open slots have a width of .75 inch. The width of the teeth at the air gap is 1 inch; the length of the single air gap .2 inch; the polar arc 5 inches, and the length of the pole parallel with the shaft 10 inches. Assuming that the total flux per pole is 2,500,000 lines (2.5 megalines), calculate the ampere-turns for the air gap, making allowance for pole and tooth fringing.

SOLUTION.—The effective polar arc is found as follows:

$$\frac{\text{pole pitch} - \text{pole arc}}{l_g} = \frac{8 - 5}{.2} = 15$$

From Fig. 15, the corresponding value of the coefficient k is 3, nearly. By the formula of Art. 52, the effective arc is $5 + 3 \times .2 = 5.6$ in. and the effective pole area is $5.6 \times 10 = 56$ sq. in. The average air-gap density is $2,500,000 \div 56 = 44,600$ lines per sq. in., approximately.

To obtain the corrected air gap, use $s = .75$; $t = 1$; and $\frac{s}{l_g} = \frac{.75}{.2} = 3.75$. From Fig. 16, the corresponding value of k' is .58. Substituting in the formula of Art. **53**,

$$l'_g = \left(\frac{1 + \frac{.75}{1}}{1 + .58 \times \frac{.75}{1}}\right) \times .2 = \frac{1.75}{1.435} \times .2 = .244, \text{ nearly}$$

From the formula of Art. **51**,

$I T_g = .313 \times 44{,}600 \times .244 = 3{,}400$ ampere-turns, approximately. Ans.

POLE PITCH, PERIPHERAL SPEED, AND FREQUENCY

54. Alternators are built for such a wide range in rotative speeds and outputs that it is practically impossible to assign any definite speeds corresponding to a given output. Machines for direct connection to high-speed reciprocating engines may range in speed from about 350 to 150 revolutions per minute, and those for direct connection to Corliss engines from 150 to 75 revolutions per minute. For turbo-alternators, the speeds are very much higher, ranging from about 500 to 3,600 revolutions per minute, depending on the type of steam turbine used. Waterwheel alternators are built for great range of speed and output, the speed being fixed largely by the available head of water for operating the wheels.

55. The **peripheral speed**, that is, the number of feet per minute traveled by the periphery of the revolving field, in alternators of ordinary construction is usually below 8,000 feet per minute. If this peripheral speed is exceeded, especial precautions must be taken in building up the rotating part. For speeds over 6,000 feet per minute, cast steel should be used for the field rim and spider in preference to cast iron, while for speeds above 8,000, it is usually necessary to build up the field rim of steel punchings, thus making a construction stronger than is possible with a cast rim. With turbo-alternators, the peripheral speed may reach 15,000 feet per minute, for which special construction of the rotating part as

described later is necessary to secure strength to withstand the enormous centrifugal stresses.

56. Relation Between Pole Pitch and Peripheral Speed.—If the pole pitch of an alternator is fixed, then, for a given frequency, there is a certain definite value of peripheral speed; or, if the peripheral speed is fixed, there is, for a given frequency, a certain fixed value of the pole pitch. This may be proved as follows: The frequency of an alter-

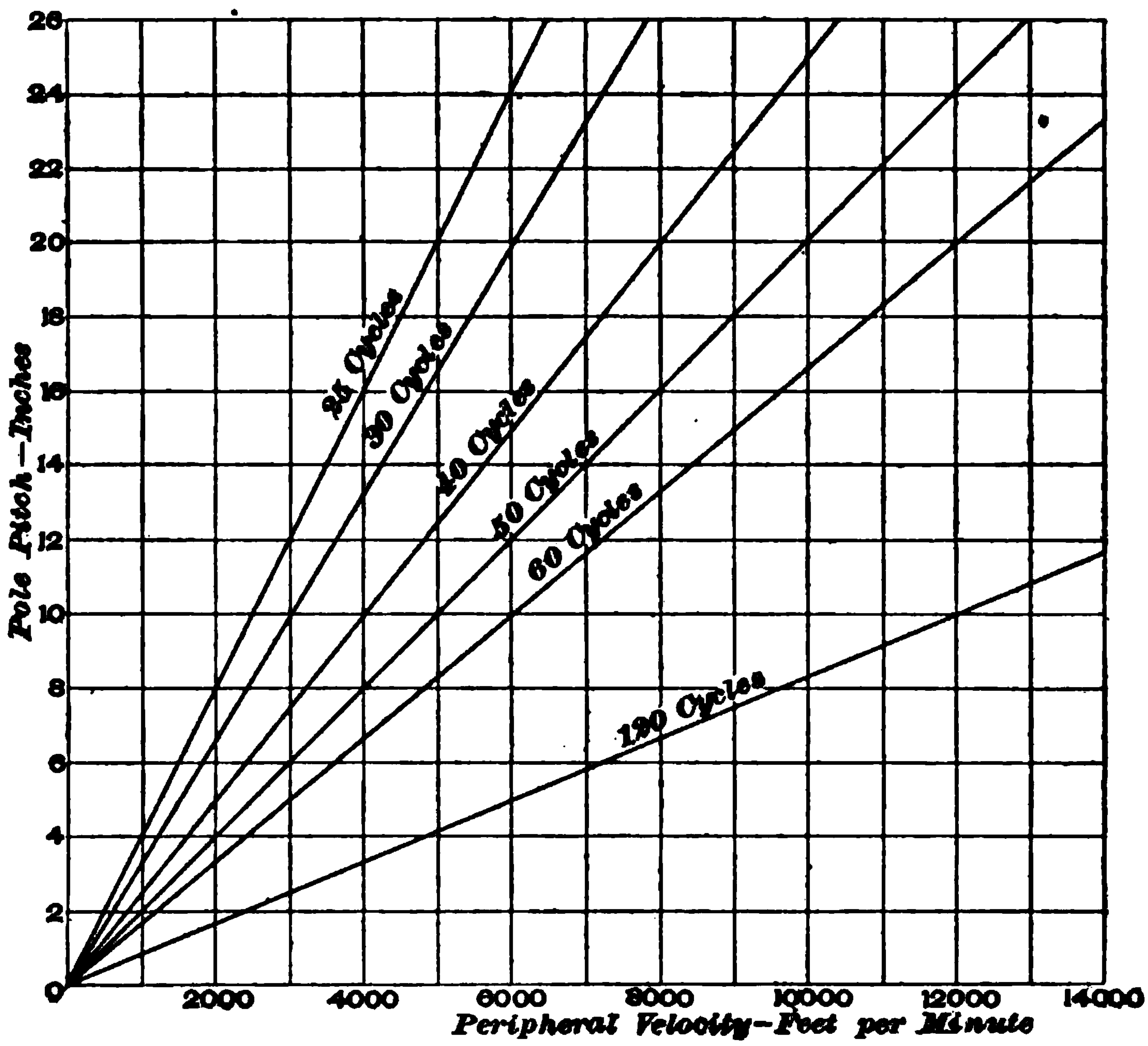


FIG. 17

nator in cycles per second equals the number of pairs of poles multiplied by the revolutions per second, or

$$n = \frac{p}{2}s, \qquad (1)$$

in which n = frequency in cycles per second;
p = number of poles;
s = revolutions per second.

Also, pole pitch in inches $= \frac{\pi d}{p}$, (2)

in which d is the external diameter, in inches, of the revolving field, and p the number of poles as before; that is, the pole pitch is the distance between pole centers measured on the circumference of the revolving field.

$$\text{Peripheral speed in feet per minute} = \frac{\pi d}{12} s\,60 \qquad (3)$$

From formula **2**, $\pi d = p \times$ pole pitch. Substituting this value of πd in formula **3** gives peripheral speed in feet per minute $= 5 p s \times$ pole pitch; but, from formula **1**, $p s = 2 n$; hence,

$$\text{peripheral speed} = 10 n \times \text{pole pitch} \qquad (4)$$

or,

$$\text{pole pitch} = \frac{\text{peripheral speed in feet per minute}}{10 n} \qquad (5)$$

If with a given frequency the pole pitch is increased, the peripheral speed must also be increased. It also follows that in machines of high peripheral speed, for example, turbo-alternators, the pole pitches are very large. Fig. 17 shows the relation between peripheral speed and pole pitch for a number of the more common frequencies; for example, a 25-cycle alternator with a 16-inch pole pitch must run at a peripheral speed of 4,000 feet per minute.

ARMATURE INSULATION

57. **The insulation of the armature conductors** must be designed with a large factor of safety, which shall be carefully carried out in order to withstand the working pressure. In alternating-current apparatus, the maximum electromotive force to which the insulation is subjected is much in excess of the value indicated by a voltmeter, because the voltmeter indicates the effective value, which is only .707 times the maximum value. Moreover, the windings are always required to withstand an insulation test between the windings and the frame, made with an alternating electromotive force much in excess of the normal voltage of the machine. It is this

high-potential test rather than the normal working voltage that determines the amount of insulating material required in the slots. Table II gives the test voltages recommended by the Committee on Standardization of the American Institute of Electrical Engineers and very generally adopted by manufacturers of electrical machinery. The test voltage is applied for 1 minute, which is amply sufficient to test the insulation; in fact, a longer application is not only unnecessary, but it may permanently injure thoroughly good insulation.

TABLE II

VOLTAGES FOR INSULATION PUNCTURE TESTS

(*A. I. E. E. Standard*)

Output of Machine	Normal Volts	Test Volts
Under 10 kilowatts .	Not exceeding 400	1,000
10 kilowatts and over	Not exceeding 400	1,500
Under 10 kilowatts .	400 to 800	1,500
10 kilowatts and over	400 to 800	2,000
Any	800 to 1,200	3,500
Any	1,200 to 2,500	5,000
Any	2,500 and over	Double the normal rated voltages.

58. Insulating Materials.—The materials commonly used for insulating the coils of alternators are mica, fullers' board, oiled cambric or linen, and horn fiber, fish paper, or similar tough fibrous material; the horn fiber or fish paper is used principally as a mechanical protection for the outside of the coil where it comes in contact with the iron of the core. When the coils are wound on formers and afterwards placed in open slots, they are completely insulated before being put in place, and no separate insulation is put in the slot itself. When closed slots are used and it is therefore necessary to push the coils, bars, or cable in from the end of the core,

the slots are often lined with an insulating tube and only part of the insulation is on the coil itself. However, the general practice now is to form the insulation on the coil whenever possible, and in some cases it is even molded under pressure around the coil.

The insulating material is usually applied in several layers and the whole coil impregnated with insulating varnish. Some makers place the insulated coils in an air-tight tank, or vacuum oven, from which the air is then exhausted. When the vacuum is so complete that the air is almost wholly removed from the many small crevices in the insulation, the insulating compound is forced into the tank under pressure and fills the openings from which the air was removed.

59. For high-pressure machines, oiled cambric and mica are the materials depended on mostly for insulation; cambric treated with insulating oil and applied carefully in overlapping layers makes an insulation that retains its good properties under long continued heating at moderate temperature. Mica has very high insulating qualities, but is expensive and difficult to apply to the coils; it is, however, frequently used on the slot portion of the coils in conjunction with oiled cambric. On low-voltage alternators, fullers' board combined with oiled cambric is used largely for insulating purposes, and if thoroughly impregnated with insulating varnish to prevent absorption of moisture, it is quite satisfactory. After the coil has been insulated, the parts that go in the slots are usually covered with a layer of horn fiber, fish paper, or leatheroid, to keep the insulation proper from being damaged when the coil is placed in the slots.

60. Thickness of Insulation.—Tests on insulating materials to determine the number of volts a given thickness will stand before breaking down are only a rough guide as to the thickness to be used on a given machine. A very large factor of safety must be allowed, because the insulation is liable to be more or less damaged while being applied, and even at best, insulating materials are of such nature

that they cannot be depended on as having uniform quality throughout.

The curves in Fig. 18 show the voltages at which different thicknesses of various insulating materials will break down when subjected to an alternating electromotive force. The results are averages of a number of tests, and individual samples might show results varying considerably from those given. The ordinates give the breakdown voltage in kilovolts (thousands of volts), and the abscissas the corresponding thickness in inches. For example, .02 inch of oiled

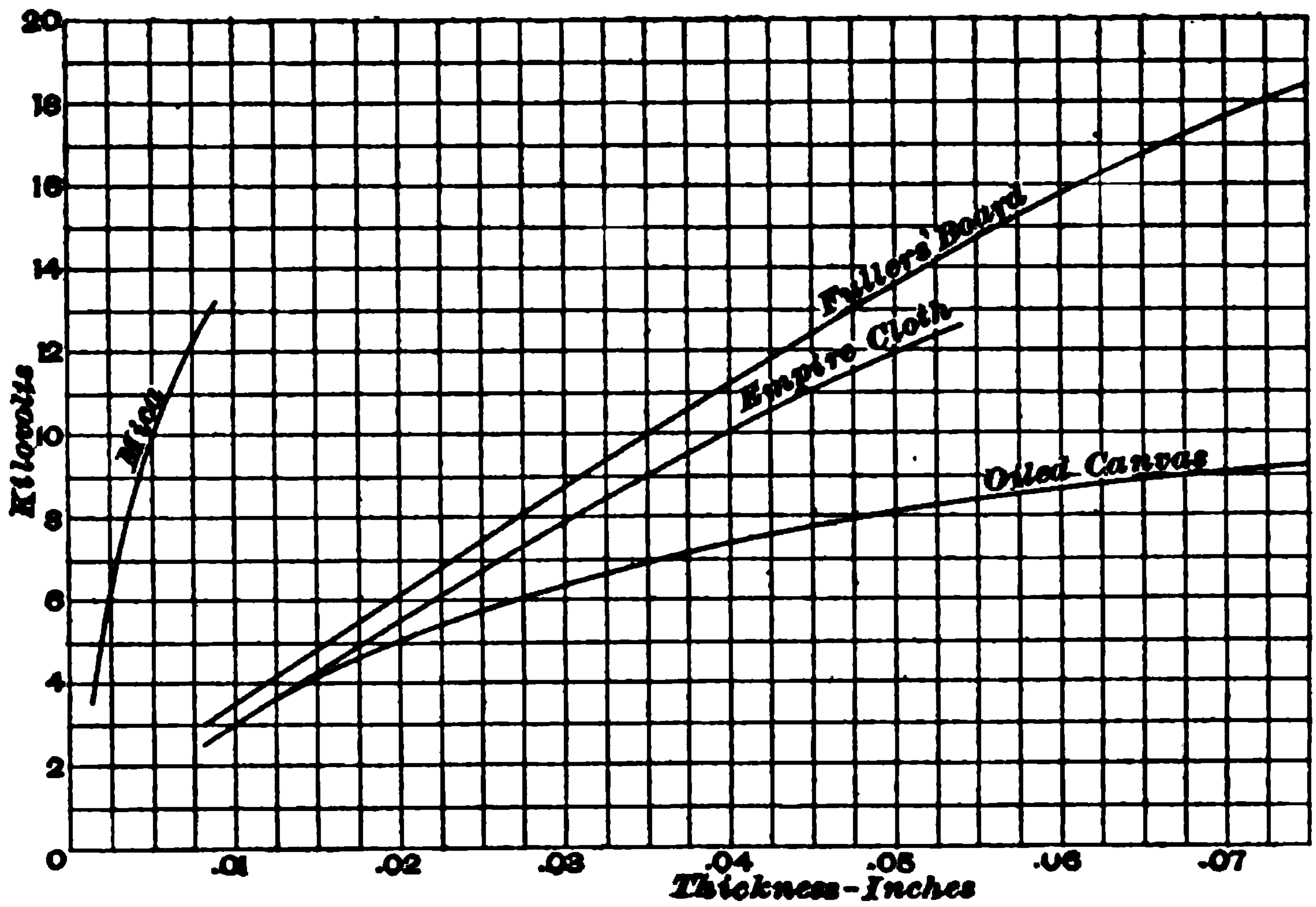


FIG. 18

canvas will stand 5,000 volts, and .04-inch Empire cloth (oiled cambric) will stand 10,000 volts. Oiled cambric is usually from 6 to 10 mils (.006 to .01 inch) in thickness and is applied in the form of tape, half-lapped, until the required thickness is obtained. For alternators, allowances of space for insulation given in Table III will usually be sufficient.

On the low voltages—110 and 220 volts—mica is seldom used; but above 440 volts, some makers use one or more layers of mica. The allowances given in Table III refer to the insulation placed on each side of a group of conductors

forming one side, or leg, of a coil, that is, each side of a 440-volt coil would have, say, .05 inch (50 mils) of insulation all around it. Also, the allowances given assume that

TABLE III

SPACE ALLOWANCE FOR ALTERNATOR SLOT INSULATION

Generated Voltage	Allowance for Insulation. Inch
110–220	.04–.05
440–600	.05–.06
1,100–2,200	.07–.08
4,400	.09–.11
6,600	.12–.13
11,000	.15–.17

one or more layers of mica are used for pressures above 440 volts. If the insulation consisted wholly of oiled cambric, it would be necessary to allow somewhat more space than given in the table.

CURRENT DENSITY IN ARMATURE CONDUCTORS

61. Cross-Section of Conductors.—The **cross-section of armature conductor** to be allowed per ampere depends considerably on the type of machine. Sufficient carrying capacity must be allowed to prevent overheating, but the heating depends as much on the ventilation as on the energy dissipated in the conductors. The rotating parts of some alternators and induction motors are provided with fans that force a strong blast of air around the conductors, thus permitting them to be worked at a high-current density without undue rise in temperature; but some power is required to drive these ventilating devices; that is, they increase the windage loss. In the case of generators wound for high voltage, with very heavily insulated coils that cannot readily dissipate the heat, the number of circular mils allowed per ampere in the armature conductor must be greater than with lightly insulated coils. The number of circular mils per ampere in

modern machines usually lies between 400 and 1,000, from 600 to 800 being very common values.

62. Ampere-Conductors per Inch.—Since the watts I^2R loss dissipated per square inch of armature surface is equal to $\frac{\text{ampere-conductors per inch}}{\text{circular mils per ampere}}$ (see Art. **11**), the number of ampere-conductors per inch, for a given value of the circular mils per ampere, must be kept low enough to avoid overheating. Again, if the number of ampere-conductors per inch is large, the armature reaction and self-induction will be high, thus tending to make the regulation poor. The number of ampere-conductors per inch in alternators and induction motors is usually from 400 to 700, a common value being about 500; if the ventilation is unusually good, the number may sometimes exceed 700, but in most cases it is advisable to keep below 600.

DESIGN OF ALTERNATING-CURRENT APPARATUS

(PART 2)

ARMATURE WINDINGS

1. So far as their electrical features are concerned, the **windings** for the stator of a rotating-field alternator are like those of an induction motor. In the alternator, a field magnet is revolved within the stator, or armature, and polyphase currents are induced in the stator windings; in the induction motor, polyphase currents are lead into the stator windings from an outside source, and a revolving magnetic field is set up. There is almost an infinite variety of windings for polyphase alternators, and the designer sometimes has to exercise considerable ingenuity in selecting the one best suited for a given machine. For example, some windings are particularly useful for high-voltage alternators, others for machines of lower voltage. There is also considerable choice in the arrangement of the coils, which may consist of a large number of turns of wire or only one turn, or loop, of copper bar. In alternators, the possible range in voltage is much greater than in direct-current machines; and also, on account of alternators being wound single-phase, two-phase, or three-phase they have much greater variety in the arrangement of coils. It will therefore be impossible to describe here all the kinds of windings, but the main features of the types most commonly used will be explained.

MECHANICAL ARRANGEMENT OF WINDINGS

2. In all modern alternating-current generators and motors, the windings are of the drum type, with the active part of the coils placed in slots. So far as the mechanical arrangement of the coils is concerned, the windings can be divided into two general classes: *chain windings* and *two-layer windings.*

A third class, used principally for small induction motors and called *basket winding*, is really a special form of chain winding. Either of the general types just mentioned may be made up of coils consisting of several turns of wire, or of coils, or winding units, each of which may have but one turn of copper bar. The ends of the one-turn, bar-wound coils may either be bent away from each other, thus forming a *wave winding*, or they may lap back over each other, as described in connection with direct-current armatures, thus forming a *lap winding.* Again, either chain or two-layer windings may have one or more slots per pole per phase; that is, the winding may be concentrated in a few slots or distributed in several slots per pole.

CHAIN WINDINGS

3. All **chain windings** have but one bunch, or layer, of conductors in each slot, and are so called from the arrangement of the end connections and the way in which the coils interlink. Each side of each coil fills one whole slot, and there are half as many coils as slots. The distinguishing features of a chain winding are shown in Figs. 1 and 2. In Fig. 1, *a* and *b* are the ends of two coils of a two-phase winding.

FIG. 1

One coil *a* projects straight out from the armature, while the other *b* is bent down in order to clear the first coil. Fig. 2 shows a three-phase chain winding having one slot per pole per phase, or three slots per pole; the bent and straight coils are clearly shown, and *a*, *a* are connections between coils.

4. Fig. 3 shows straight and bent coils for a three-phase chain winding with one slot per pole per phase. The types of coils shown in Fig. 4 are for a three-phase winding having two slots per pole per phase. The parts of the coils that project beyond the slots are heavily taped, while, in addition

Fig. 2

to the slot insulation, the parts lying in the slots are protected by an outer layer of leatheroid or other tough material.

Fig. 5 shows a special form of chain winding. The armature conductors are joined by involute connections arranged in two layers so as to clear each other where they cross.

5. Fig. 6 shows a number of coil arrangements for chain windings. At (*a*) is a single-phase winding in which there are three slots per pole with only two slots occupied by conductors. This style of winding is frequently employed for single-phase machines. When this winding is used, one slot per pole may be empty without interfering with the operation of the machine; also, three-phase punchings may be used for single-phase windings.

At (*b*) is a three-phase chain winding with three slots per pole, the same as shown in Fig. 2; the coils of each phase are here given a distinctive color, phase *1* being black, phase *2* red, and phase *3* blue. Taking the vertical dotted lines as representing the pole centers, it will be seen that the corresponding conductors of each phase are 120 electrical degrees apart. For example, the left side of a coil of phase *2* is 120°, or one-third the distance from *N* to *N*, away from the left side of a coil of phase *3*.

FIG. 6

6. Different arrangements of coils for two-phase chain windings with four slots per pole are shown in Fig. 6 (*c*), (*d*), and (*e*). Since 4 is not divisible by 3, four slots per pole is not suitable for three-phase windings. The winding shown in (*c*) is preferable to (*d*) or (*e*), because the coil end connections are shorter and there are only two differently shaped coils, thus requiring only two coil formers; (*d*) requires three coil formers and (*e*) four. Omitting either phase in (*c*)

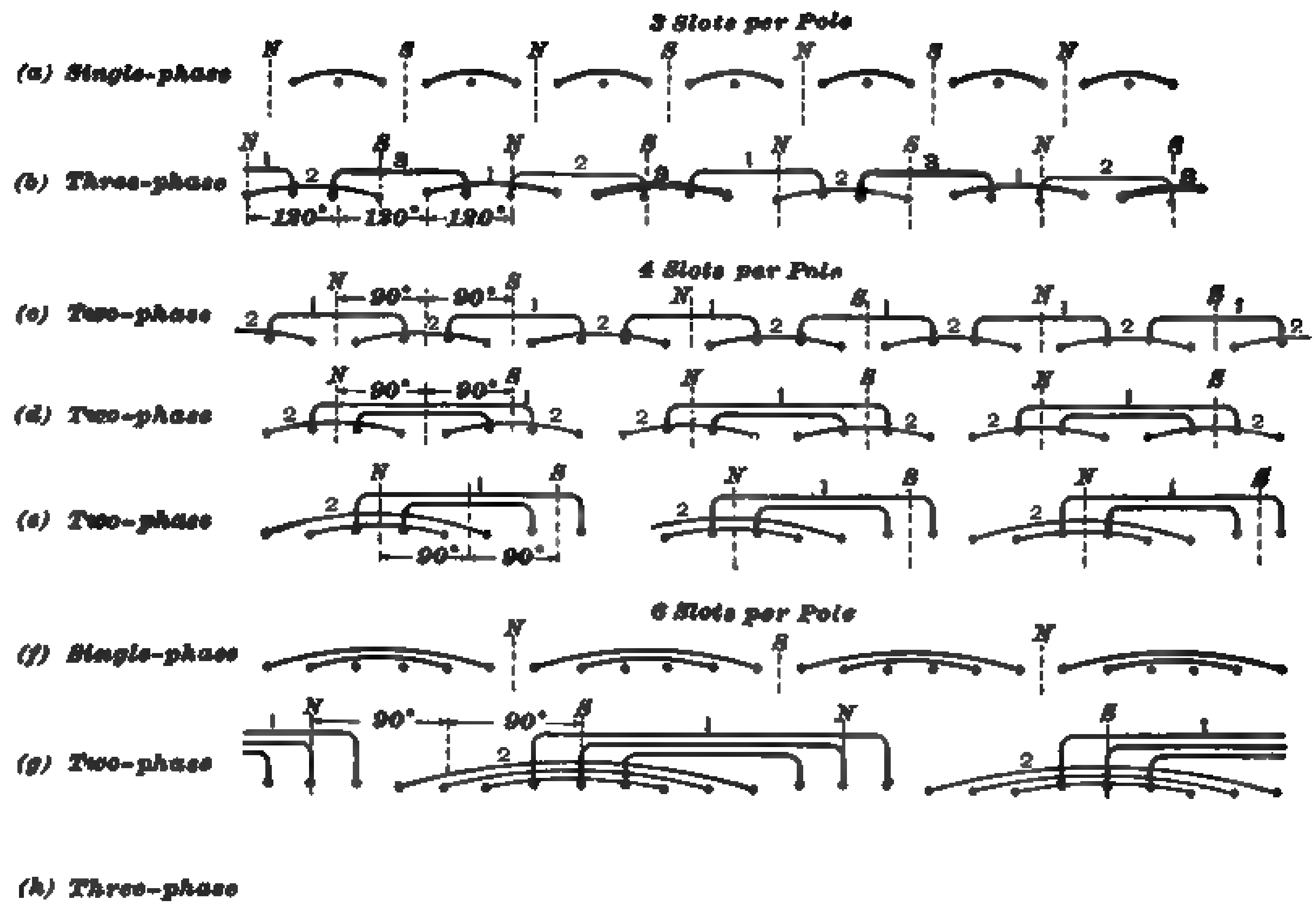


FIG. 6

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would result in a single-phase winding with two occupied slots per pole.

Chain windings with six slots per pole are shown in (*f*),

FIG. 4

FIG. 5

(*g*), and (*h*). In the single-phase winding (*f*), four slots per pole are filled and the other two are empty. The two-phase

winding (*g*) requires six coil formers, and the end connections of some of the coils are rather long. The three-phase winding (*h*) has two turns per pole per phase.

7. Basket Winding.—**Basket winding** is a special form of chain winding in which all coils are of the same shape and cross one another at the ends of the stator, as shown in Fig. 7. This winding has only one layer, and there are half as many coils as there are slots. Basket winding is used almost wholly for small induction motors in which the voltage is low and the difficulties of insulation not great.

8. Advantages and Disadvantages of Chain Windings.—The chief advantage of the chain type of winding is that it admits of high insulation, and for pressures of over 4,400 volts, it is practically the only kind admissible, with the exception of involute windings as shown in Fig. 5. The

Fig. 6

ends of the coils of a chain winding can be kept widely separated, so that there is little danger of the coils coming into contact with each other. Chain windings have the disadvantage that all coils are not alike in form or resistance, and such windings usually require several formers to make up the coils for an armature.

TWO-LAYER WINDINGS

9. The distinguishing feature of **two-layer windings** is that each slot contains two groups of conductors, and, therefore, there are as many coils, or winding units, as there are slots. The term *layer* does not refer to the number of layers of conductors in each coil, but rather to the arrangement of the coils themselves. All coils are of the same form, and the winding is perfectly symmetrical throughout. Fig. 8 illustrates a portion of a typical two-layer winding, showing the upper and lower layers distinctly. There is only one conductor in the upper part of the slot and one in the lower

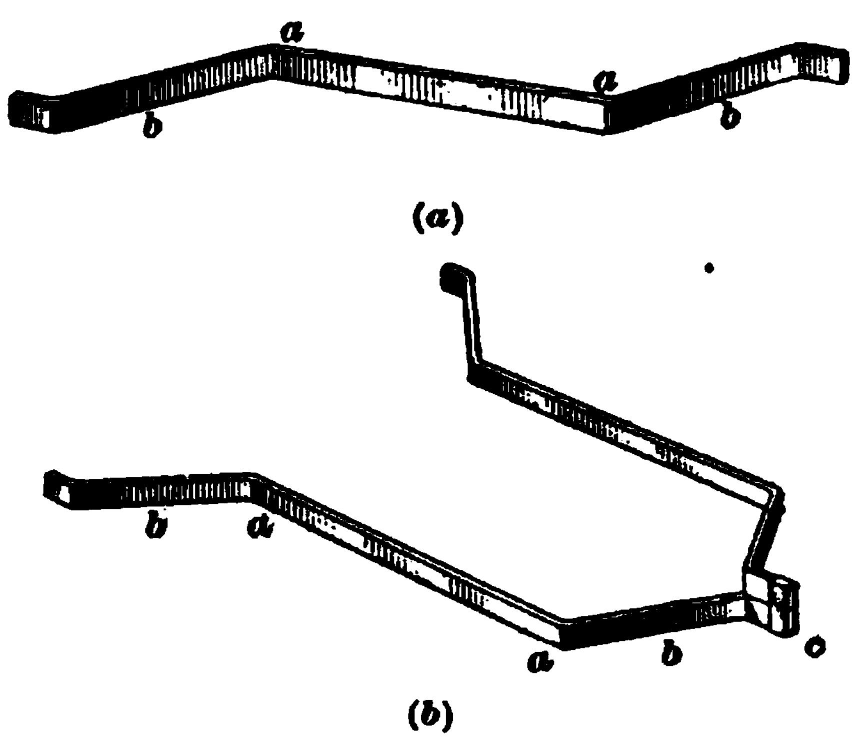

FIG. 9

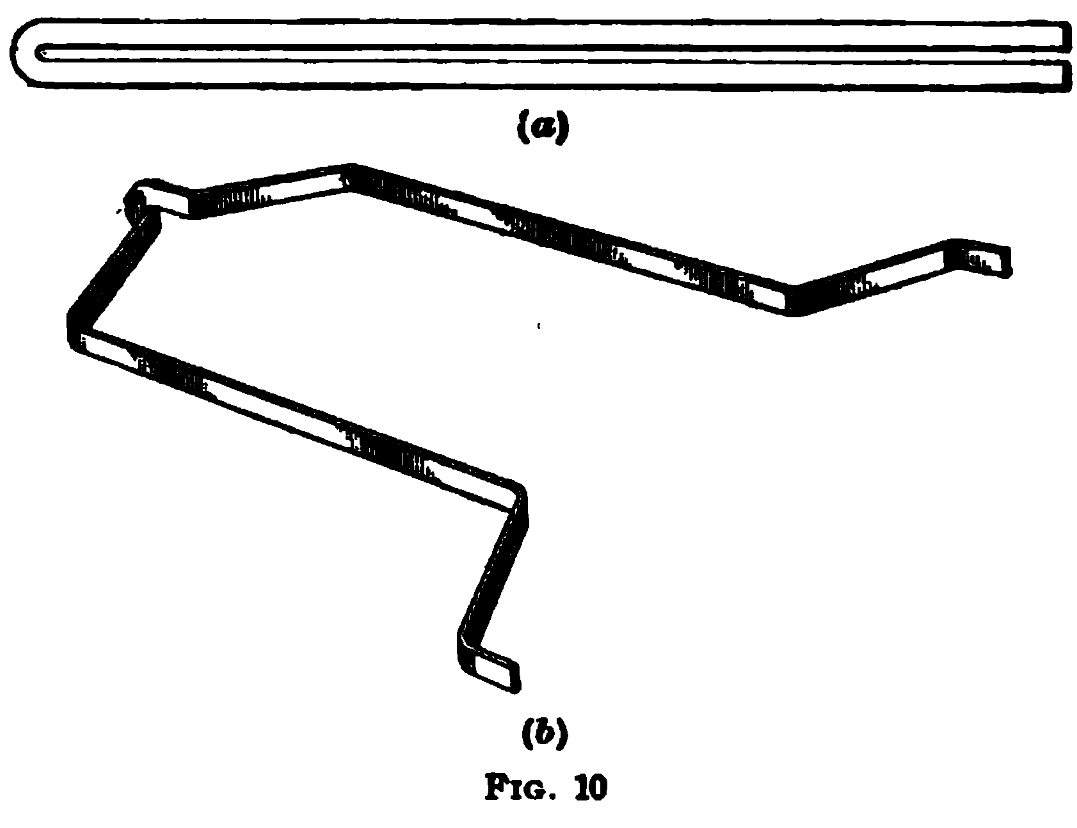

FIG. 10

part, each consisting of three strips in parallel bound together with tape.

10. Fig. 9 shows one method of making up coils, or winding units, for a two-layer, bar-wound armature. The copper bar is bent as shown at (*a*), the part *a a* forming

the active conductor in the slot and *b b* the end connections. Two of these bars are joined together by a soldered clip *c*, as shown in (*b*), to form a loop or coil. Another method is indicated in Fig. 10. Here, the bar is first bent into a long loop, as shown at (*a*), and then pulled out, as shown at (*b*). This is the method by which the coils shown in Fig. 8 are formed.

If the coils for a two-layer winding consist of several turns, they are wound on formers and insulated in the same manner as chain windings. Fig. 11 shows four coils for this

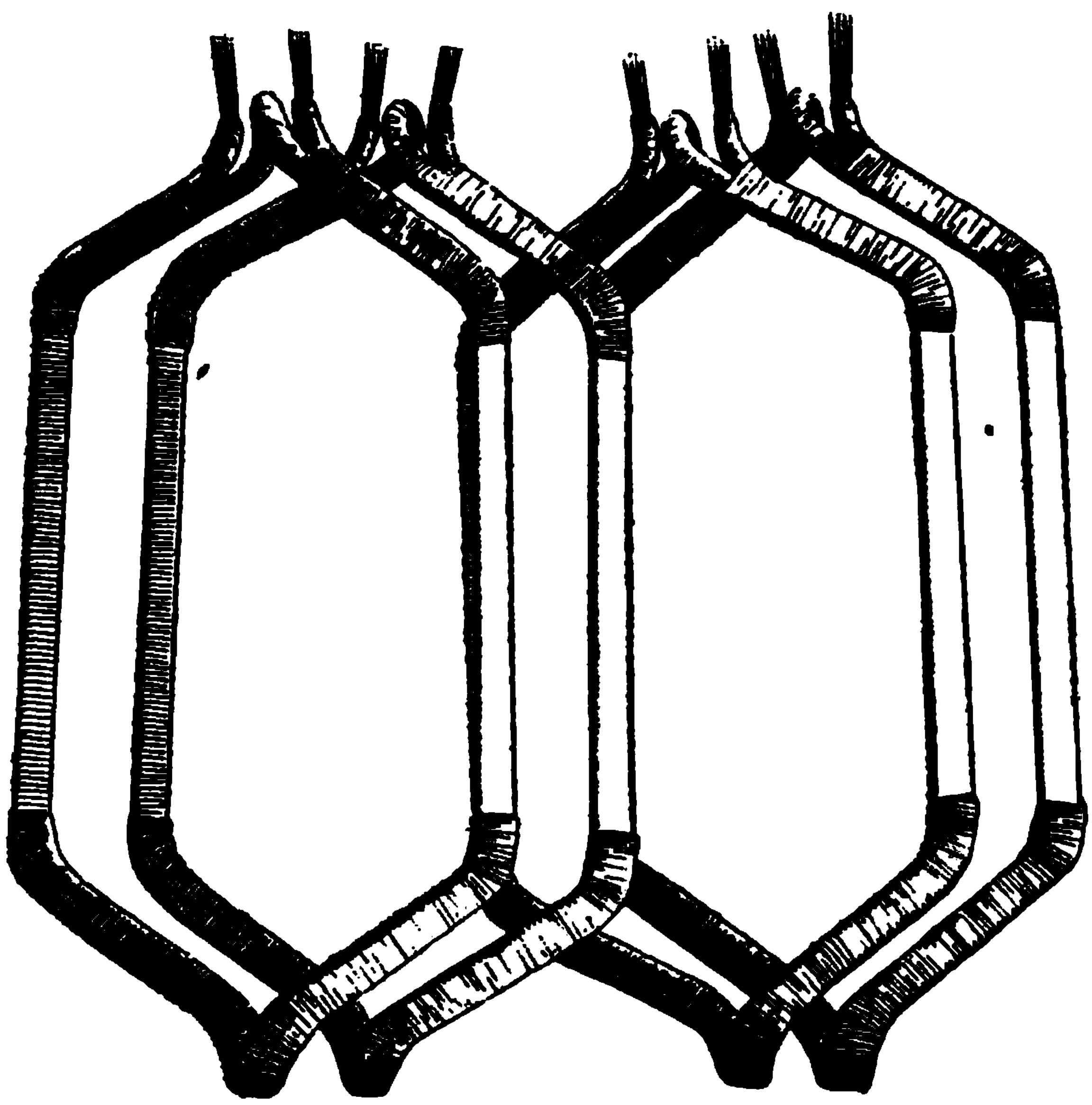

FIG. 11

type of winding, and also illustrates how the two-layer arrangement allows the end connections to be arranged systematically and cross each other without interfering. In this case, each coil consists of two turns of conductor made up of three thin strips in parallel.

11. Advantages and Disadvantages of Two-Layer Windings.—Two-layer windings are particularly suitable for machines having a comparatively large number of coils

and slots and wound for relatively low voltage. They are widely used for induction motors, and also for alternators that have sufficient room in the slots for the extra insulation required for this winding. The ends of the coils of a two-layer winding cannot be so widely separated as can the ends of the coils of a chain winding. Moreover, since the full generated electromotive force exists between upper and lower layers in the slots, the insulation between layers must be very thorough; and, since the coil has uniform insulation on all sides, it follows that when one layer is placed over the other in the slot there is double insulation between the layers. This provides good insulation, but it takes up valuable slot space that is available for the conductors with a chain winding. Because of the greater amount of slot space needed for insulation, the two-layer winding is not so appropriate for high pressures as the chain winding.

ELECTROMOTIVE FORCE GENERATED IN THE WINDINGS

12. When an alternating magnetic flux Φ is made to vary through a number of turns T connected in series, at the rate of n cycles per second, the effective electromotive force generated is

$$E = \frac{4.44\,\Phi\,T n}{10^8}$$

This formula assumes that the generated electromotive force follows a sine wave and that all turns are active at the same instant; that is, they are all cut simultaneously by the flux.

13. Single-Phase Distributed Winding.—If the winding is subdivided or distributed, the electromotive forces in all turns of a given coil do not reach their maximum value at the same instant, and, for a given number of turns, the electromotive force is less than would be obtained with a bunched, or concentrated, winding. In Fig. 12 is shown a portion of an armature with a single-phase winding having one slot per pole. It is assumed that the electromotive

forces in the conductors under the N poles are directed upwards toward the reader, as denoted by the letter U, and those under the S poles downwards, as denoted by the letter D. The slots are 180 electrical degrees apart, and since there is only one slot under each pole, the conductors

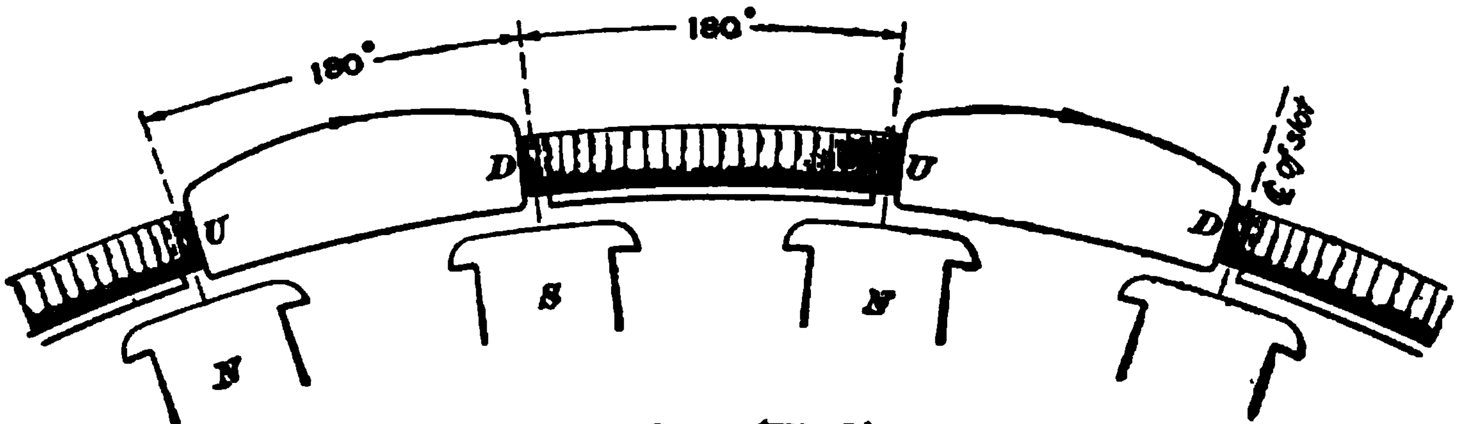

FIG. 12

are closely bunched together and all the electromotive forces reach their maximum values at the same instant. When the coils are connected in series, the total electromotive force is given by the formula of Art. 12, T being the total number of turns in series.

Fig. 13 shows a single-phase winding with two slots per pole, the centers of the slots being 60 electrical degrees, or

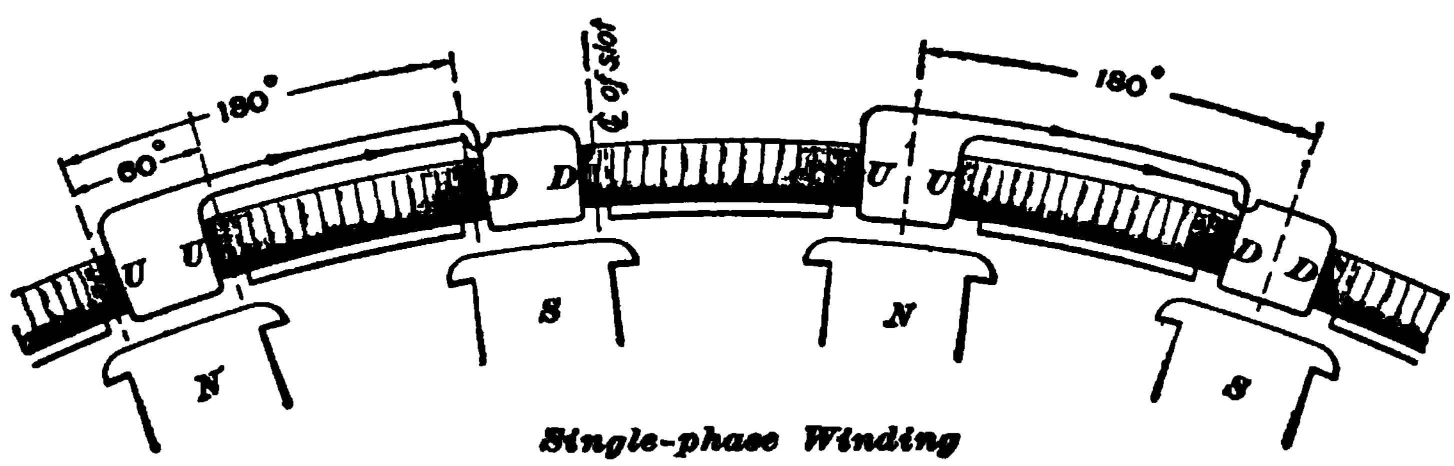

FIG. 13

one-third the pole pitch, apart. There are now twice as many coils as before (Fig. 12), but if the total number of turns on the armature is kept the same, the number of turns per coil will be half as much. The electromotive forces in the conductors of the two coils under a given pole will be displaced 60° in phase; and since the number of conductors per slot or turns per coil is half as great, the total

electromotive force $E_1 = E_2$ for each of the two sets of coils will be

$$E_1 = E_2 = \frac{4.44\,\Phi\,T n}{10^8} \times \tfrac{1}{2},$$

in which T is the *total* number of turns on the armature.

If all the turns are connected in series, the total electromotive force will be the resultant found by combining the electromotive forces of each set, as shown in Fig. 14, where $O a$ represents the electromotive force E_2 in one set and $O b = E_1$ that in the other, the two differing in phase by an angle of 60°. The resultant of the two forces is $O c$, which

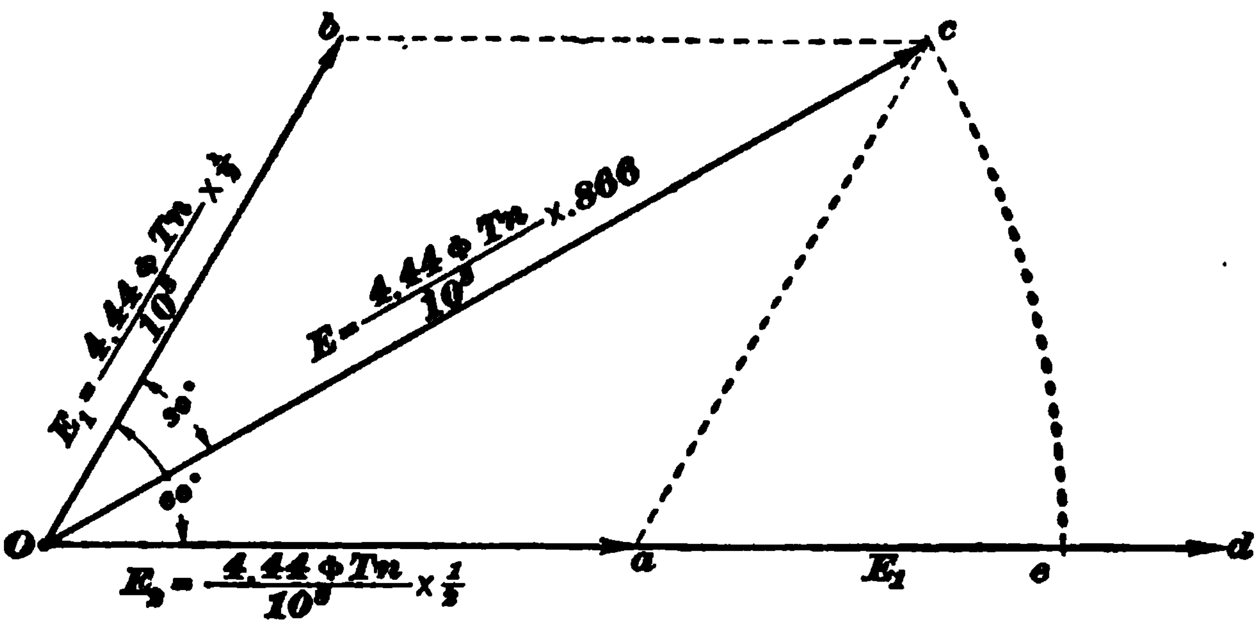

FIG. 14

is the electromotive force E obtained when all the coils are connected in series. This is

$$E = 2\left(\frac{4.44\,\Phi\,T n}{10^8} \times \tfrac{1}{2}\right)\cos 30° = \frac{4.44\,\Phi\,T n}{10^8} \times .866$$

If the winding were not distributed, the total electromotive force would be $O d = O a + a d$, $a d$ being made equal to $O b$. The resultant $O c = O e$; hence, the reduction in voltage by distributing the winding is $e d$.

If the winding were subdivided into three slots per pole, and the total number of turns kept the same as before, the resultant electromotive force would be found as shown in Fig. 15. The three electromotive forces E_1, E_2, and E_3 differ 60° from one another in phase, and as each equals $\frac{4.44\,\Phi\,T n}{10^8}$ $\times \tfrac{1}{3}$, the resultant electromotive force $O d$ is

$$E = \frac{4.44\,\Phi\,T n}{10^8} \times .667$$

14. Polyphase Distributed Windings.—In **polyphase windings**, the distribution of the coils in two or more slots per phase always reduces the electromotive force for a given number of turns, but since the distance between

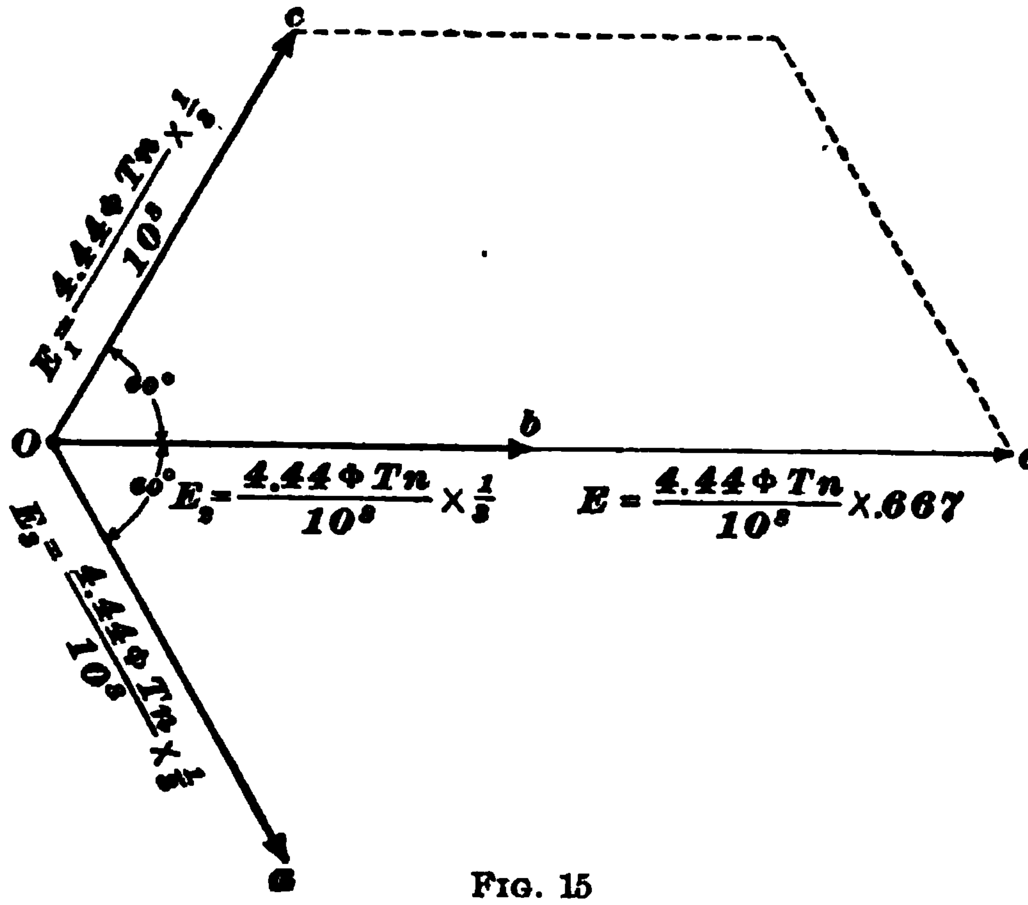

FIG. 15

slots is not large, the reduction in voltage is not very great. For example, in a three-phase winding with two slots per pole per phase, there will be six slots per pole, and the slots will be 30 electrical degrees apart. The electromotive forces E_1 and E_2 of each group of coils will therefore be combined

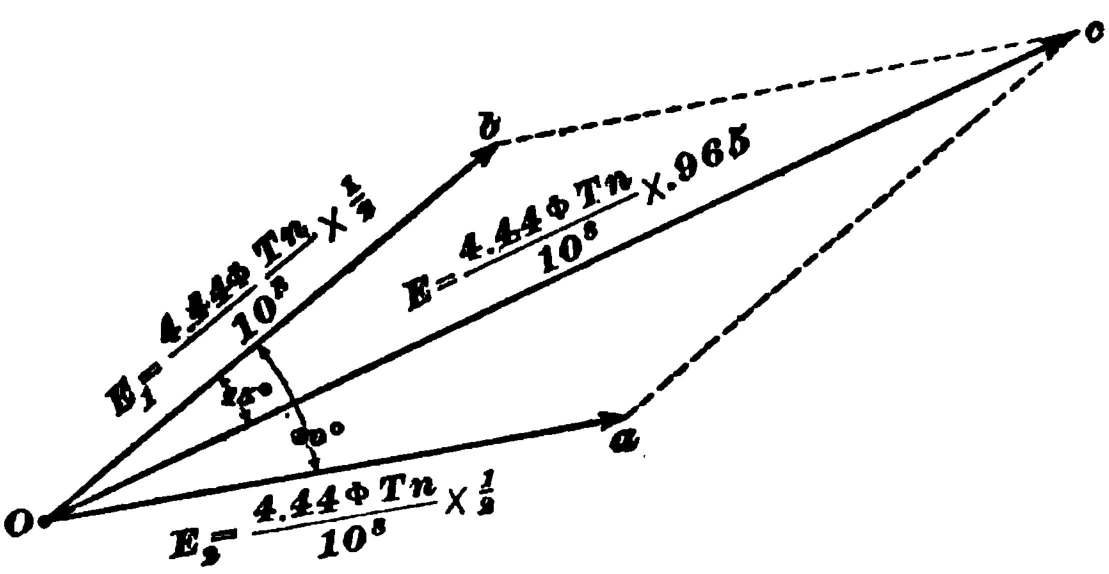

FIG. 16

as shown in Fig. 16; and if there are T turns per phase, the resultant will be

$$Oc = 2\left(\frac{4.44\ \Phi\ Tn}{10^8} \times \tfrac{1}{2}\right)\cos 15^\circ = \frac{4.44\ \Phi\ Tn}{10^8} \times .965$$

The arrangement of the winding in two slots per pole per phase has therefore reduced the voltage, for a given total number of turns, only 3½ per cent. (100 − 96.5).

15. General Formula for Electromotive Force. In order to take account of the winding distribution in any given case, the electromotive force given by the formula of Art. 12 for a single slot or concentrated winding must be multiplied by a factor that corrects for the distribution, and, for any winding, the formula is written as follows:

$$E_p = \frac{4.44\,\Phi\,T_p\,n}{10^8} \times k_w$$

in which E_p = effective volts generated per phase;
Φ = flux per pole;
T_p = total number of turns in series per phase;
n = frequency, in cycles per second;
k_w = a factor depending on the way in which the winding is distributed in the slots.

Table I gives the values of k_w for a few of the more common types of winding. These values are obtained for any given winding, as previously explained. When there is only one slot per pole per phase, the value of k_w is unity.

TABLE I

VALUES OF WINDING FACTOR k_w

Style of Winding	Value of k_w
Single-phase, with two slots per pole (slots 60° apart)	.866
Single-phase, with three slots per pole (slots 60° apart)	.667
Two-phase, two slots per pole per phase	.924
Two-phase, three slots per pole per phase	.912
Two-phase, four slots per pole per phase	.908
Three-phase, two slots per pole per phase	.965
Three-phase, three slots per pole per phase	.960
Three-phase, four slots per pole per phase	.958

16. Distributing a winding in more than four slots per pole per phase causes very little reduction in the value of k_w.

If a single-phase winding is made by taking two-phase armature punchings and utilizing only half the slots, that is, using only one of the phases, the value of k_w is the same as given for two-phase windings. In the same way, if only one phase of a three-phase machine is used and two-thirds of the slots left empty, the value of k_w is the same as for three-phase windings. If, however, two-thirds of the slots are filled, two of the three phases are in series, forming a single-phase winding; also, if T_p is the total number of turns of winding considered as single phase, $\frac{1}{2}T_p$ will be the number of turns in each of the phases of the corresponding three-phase winding having electromotive forces differing in phase by 120°. The electromotive force E of each phase of the three-phase winding would be

$$E_1 = \frac{4.44\,\Phi\,\frac{1}{2}\,T_p\,n}{10^8} \times k_w$$

and their resultant would be

$$E = E_1\sqrt{3} = \frac{4.44\,\Phi\,\frac{1}{2}\,T_p\,n}{10^8} \times k_w \times \sqrt{3}$$

Therefore,

$$E = \frac{4.44\,\Phi\,T_p\,n}{10^8} \times k_w \times .866$$

Hence, if a single-phase winding is made by using two-thirds of the slots of a three-phase winding, the values of k_w as given for the three-phase winding must be multiplied by $\frac{\sqrt{3}}{2} = .866$. For example, the single-phase winding shown in Fig. 13 is in two slots per pole, the slots being 60° apart. If this armature punching had another slot per pole, it would answer for a three-phase winding with one slot per pole per phase, so that the arrangement of coils is the same as if a three-phase armature were utilized and one-third of the slots left empty. The three-phase armature using this punching would have one slot per pole per phase, and since with one slot per pole $k_w = 1$ and the single-phase winding utilizes two-thirds of the slots, the value of the winding factor for the single-phase winding will be $k_w \times \frac{\sqrt{3}}{2} = k_w \times .866 = .866$, or the same

result as shown in Fig. 14. Single-phase machines are frequently made by using existing two- or three-phase armature punchings, and the foregoing remarks regarding the winding factor in such cases are important.

EXAMPLE.—A 60-cycle, 3-phase alternator has 9 slots per pole and a flux per pole of 2,000,000 lines. If there are 180 turns per phase, what is the electromotive force generated per phase?

SOLUTION.—There are 9 slots per pole, or 3 slots per pole per phase; hence, $k_w = .96$; $\Phi = 2{,}000{,}000$; $T_p = 180$; and $n = 60$. Therefore, from the formula of Art. 15,

$$E_p = \frac{4.44 \times 2{,}000{,}000 \times 180 \times 60}{10^8} \times .96 = 921 \text{ volts, approximately.}$$

Ans.

It should be particularly noted that the formula of Art. 15 gives the volts per phase, and that this may or may not be the no-load terminal voltage of the machine, since the latter depends on the manner of connecting the windings to the terminals.

WINDING CONNECTIONS

17. The principles governing the connections of the phases for polyphase windings were explained in *Alternators*. However, a few points relating to the general design of windings will be explained, and some illustrations of complete winding diagrams will be given.

18. Interconnecting the Phases of a Three-Phase Winding.—The common methods of **interconnecting** the phases of a three-phase winding are shown in Fig. 17; (*a*), (*b*), and (*c*) being Y connections, and (*d*), (*e*), and (*f*) Δ connections. Connections (*a*) and (*d*) are most commonly used, but cases sometimes arise where it is necessary to use the others, particularly with low-voltage machines having large current output. In (*a*), the coils of each phase are connected in series and the three phases are connected Y, forming a single-circuit Y winding; (*d*) is a single-circuit Δ winding. As a general rule, when the conditions will permit its use, the Y method of connection is preferable to Δ method. For a given electromotive force between line terminals T_1, T_2, T_3,

the Y-connected armature requires fewer turns per phase than the Δ-connected armature; hence, there is a smaller amount of slot space occupied by insulation. Again, with the

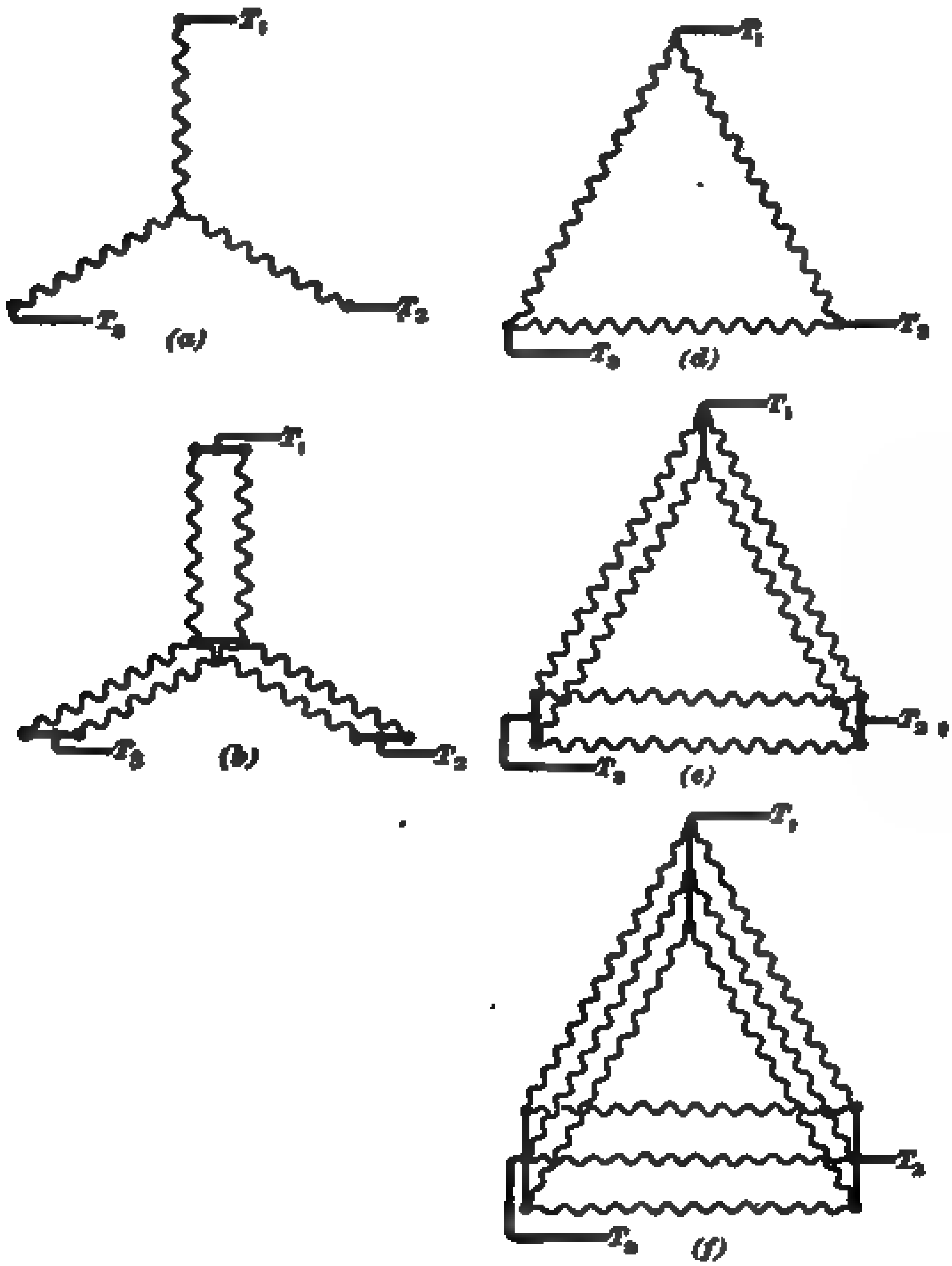

FIG. 17

Δ connection, the phases form a closed circuit within the machine, and if the electromotive forces are unbalanced, a local current may circulate in the armature, thus causing undue heating of the conductors.

19. The method of connection to be used in any given case is decided largely by the voltage and current capacity required. Generally, there is little difficulty in using the single-circuit Y connection for fairly high-voltage armatures. An alternator may have so many poles and slots that the use of a single conductor per slot—the least number possible to use—will produce too much voltage when all the conductors of a phase are connected in series. In such a case, the Δ connection or the two-circuit Y connection, Fig. 17 (*b*), should be used in preference to the single-circuit Y connection.

In the two-circuit Y connection, the coils of each phase are divided into two groups, each consisting of an equal number of coils connected in series, and the two groups are connected in parallel, thus halving the effective number of turns per phase but doubling the current-carrying capacity. In a similar manner, the coils can be connected in three parallel groups, as in Fig. 17 (*c*), forming a three-circuit Y winding, provided the number of coils per phase is divisible by 3. The corresponding two-circuit and three-circuit Δ connections are shown in (*e*) and (*f*). Whenever coils are placed in parallel on an armature, only those in which the electromotive forces are in phase can be so connected; that is, the connected coils must occupy corresponding slots, and corresponding terminals must be connected together. Three-circuit windings are seldom required, but the two-circuit connections are often very useful, especially where an existing frame with a fixed number of slots must be wound for a voltage considerably lower than that for which the machine was originally designed.

20. Two-Phase, Two-Layer Winding.—Fig. 18 shows a diagram of a typical **two-phase two-layer winding** for six poles and two slots per pole per phase; one phase is shown in red and the other in black. Each coil contains more than one turn, so that it appears to be closed on itself. Only two leads issue from each coil, and all the coils in each phase are connected in series in such a manner that the

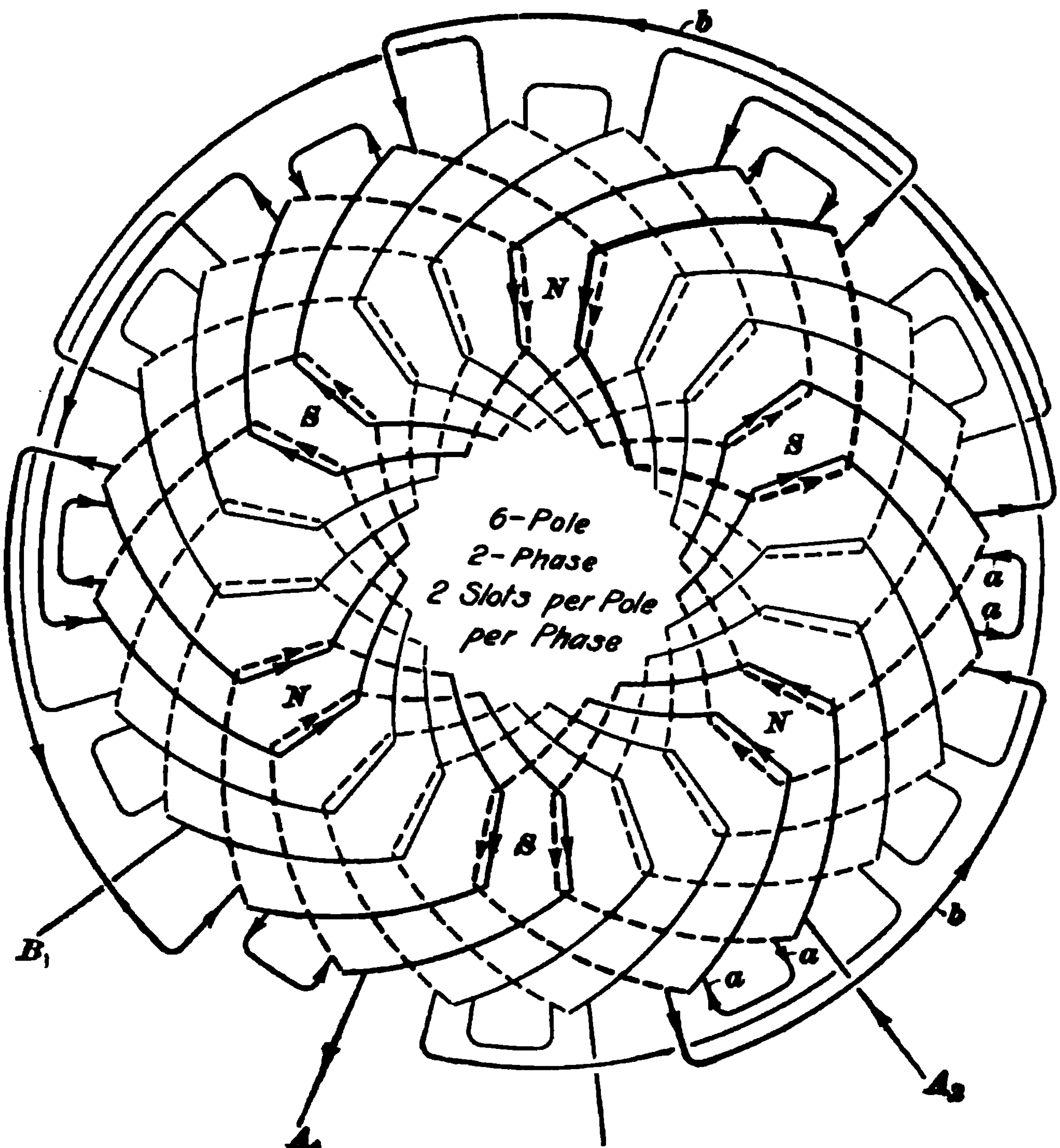

FIG. 18

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FIG. 19

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electromotive forces under the different poles will be added. Both phases are connected in exactly the same manner, $A_1 A_2$ being the terminals of one phase and $B_1 B_2$ those of the other; the two phases are not electrically connected in any way. In the diagram, the black phase is assumed to be squarely under the poles, so that the electromotive force in this phase is at its maximum. The electromotive force in the red phase is zero; hence, no arrowheads are shown on the conductors. The two coils under each pole are connected in series by the short connections, or stubs, a, a, and then joined in series with the pair under the next pole by long connections b, b.

21. Three-Phase, Two-Layer Bar Winding.—Fig. 19 shows a **three-phase, two-layer bar winding** for eight poles and two slots per pole per phase. The lower layer of conductors is shown dotted, and the three phases are colored red, blue, and black, respectively. The armature has forty-eight slots, each phase having sixteen slots and thirty-two conductors. A_1 is the beginning of the black phase, and by following the winding around from A_1 all the black conductors are passed through before the end A_2 is reached. B_1 is the beginning of the red phase, 120 electrical degrees from A_1, and B_2 is the end of the red phase. In the same way, C_1 and C_2 are the beginning and end, respectively, of the blue phase. Taking the instant when the electromotive force in the black phase is at its maximum value, that is, when the black conductors are directly under the pole centers, the electromotive forces in the other two phases will be half as great and in the opposite direction in regard to the neutral point of the winding. However, under any given pole, all the electromotive forces must be in the same direction, as indicated by the arrowheads. If terminals A_2, B_2, and C_2 are joined to a common connection, thus forming a Y winding, the direction of the electromotive forces in regard to the neutral will be correct, because the electromotive force of the black phase is at its maximum and directed toward the neutral, while those in the other two phases are directed

away from the neutral. This condition must be met as explained in *Alternators*. Bar windings similar to Fig. 19 are very frequently used for machines of comparatively low voltage and large current output, where two conductors per slot are sufficient for the generation of the required electromotive force. The winding is of the wave type, since it zigzags around the armature and does not lap back on itself. The conductors for this kind of winding would be like those shown in Fig. 8 or Fig. 9.

22. Three-Phase, Two-Layer Coil Winding. Fig. 20 shows a complete winding diagram for a three-phase armature having six poles and three slots per pole per phase, or fifty-four slots altogether. The coils of each phase occupy eighteen slots, with two layers, or two sides of coils, in each slot. Each phase consists of eighteen coils connected in series. The winding appears different from the bar winding shown in Fig. 19, but it is practically the same, except that in the winding shown in Fig. 19, the end connections of the bars themselves serve to join the winding units in series, whereas, in the winding shown in Fig. 20, the coil ends, or terminals, are joined as shown by the connecting wires around the outer part of the diagram. The coils for each phase and pole are joined in series by the short stub connections *a*, *a*, and these groups are connected in series by the long connections running from pole to pole. The terminals $A_1 A_2$, $B_1 B_2$, and $C_1 C_2$ of the three phases are Y-connected, in the same manner as described for Fig. 19. If the three phases in Fig. 20 were to be Δ-connected, C_2 would be joined to A_1, A_2 to B_1, and B_2 to C_1. The Y and Δ connections are shown diagrammatically by the small sketches in Fig. 20, and T_1, T_2, and T_3 are the line terminals in each case.

23. Polyphase Chain Windings.—The connections for chain windings are the same in principle as those for two-layer windings, but are somewhat simpler to follow out because of the more distinct arrangement of the coils. Fig. 21 shows a development of a **two-phase chain winding** for eight poles, with three slots per pole per phase.

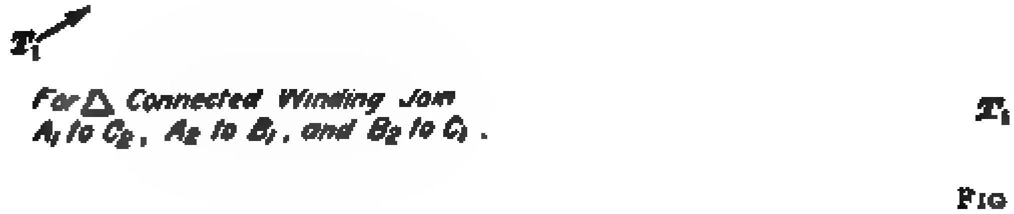


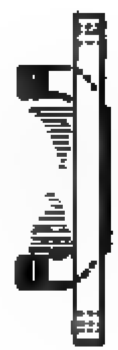
FIG. X

x_2

x_2 x_0 x_1

Two-Phase Three Slots per Pole, per Phase

Fig. 21



Three-Phase Two Slots per Pole, per Phase
Y-Connected

Fig. 22

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The three coils under each pole are connected in series and then joined to the corresponding coils under the next pole. The two phases are entirely independent and have no electrical connection with each other; A_1, A_2 being the terminals of one phase and B_1, B_2 those of the other.

FIG. 23

Fig. 22 shows the connections for a **three-phase chain winding** having two slots per pole per phase and also arranged for eight poles. In both Fig. 21 and Fig. 22, the coils of each phase are shown in a distinctive color. In

Fig. 21, the coils of the red phase are displaced 90 electrical degrees behind those of the black phase, while in Fig. 22 the three sets of coils are shifted 120°. The three-phase winding is Y-connected, terminals A_1, B_1, C_1 being joined to a common point. The windings are shown developed; in their true position, wire a at one end of the diagram connects to wire a at the other end, thus completing the blue circuit.

Fig. 23 shows part of a three-phase armature having a chain winding with three slots per pole per phase. With the exception of three slots per pole instead of two, this is the same as the winding shown in Fig. 22. In Fig. 23, the connections a, a between the coils of each group are shown.

OUTPUT, AND ARMATURE DIMENSIONS

24. In working out the design of an alternator, it is first necessary to obtain an approximate idea as to the dimensions of the armature. Having decided on these, the windings can be calculated and the probable performance determined. By working over a number of designs, the designer can soon decide which will give the best results, and the original approximate armature dimensions can be modified as may seem most desirable.

The main dimensions of the armature are its face diameter (diameter at the air gap) and the length of the laminated core measured parallel with the shaft. To obtain these dimensions the following output formula, somewhat similar to that for direct-current machines, may be used:

$$E_p = \frac{4.44\, \Phi\, T_p\, n}{10^8} \times k_w = \frac{2.22\, \Phi\, Z_p\, n}{10^8} \times k_w \qquad (1)$$

in which Z_p, the number of conductors per phase, is two times the number of turns, or $2\,T_p$. $T_p = Z_p \div 2$, and, by substitution and cancelation, the formula as given is obtained.

Calling I_p the current per phase and m the number of phases, the watts W delivered by the armature on non-inductive load will be

$$W = m\, E_p\, I_p \qquad (2)$$

This formula neglects the loss in the armature windings, but this need not be considered in making preliminary calculations. By substituting in formula **2** the value of E_p obtained from formula **1**,

$$W = \frac{2.22\, m\, k_w\, \Phi\, Z_p\, n\, I_p}{10^8} \qquad (3)$$

The frequency $n = \frac{p}{2} \times s$, where p is the number of poles and s the number of revolutions per second. If S, the revolutions per minute, is used, $n = \frac{p}{2} \times \frac{S}{60} = \frac{p\,S}{120}$.

Also the flux Φ per pole is equal to the pole area multiplied by the average magnetic density in the air gap; that is,

$$\Phi = \mathbf{B}_g \times \frac{\pi\, d\, l\, \%}{p} \qquad (4)$$

in which $\mathbf{B}_g$ = average air-gap density, in lines per square inch;

d = diameter of armature face, in inches;

l = length of laminated iron core parallel with the shaft;

$\%$ = ratio of pole arc to pole pitch; that is, the fractional part of the armature covered by the poles.

Also, in formula **3**, $m\, Z_p\, I_p$ = total ampere-conductors on the armature = $K \pi d$, where K is the ampere-conductors per inch of armature periphery. Substituting the values of n, Φ, and $m\, Z_p\, I_p$ in formula **3**,

$$W = \frac{2.22\, k_w \times K \pi d \times \mathbf{B}_g \dfrac{\pi\, d\, l\, \%}{p} \times \dfrac{p\,S}{120}}{10^8}$$

or,

$$W = \frac{2.22\, k_w\, \pi^2\, d^2\, \mathbf{B}_g\, l\, \%\, K\, S}{10^8 \times 120}$$

Therefore,

$$W = \frac{k_w\, d^2\, l\, \%\, \mathbf{B}_g\, K\, S}{5.48 \times 10^8} \qquad (5)$$

25. For a given type of alternator, k_w, $\%$, $\mathbf{B}_g$, and K are all fairly constant, so that the output in watts is proportional to the square of the armature diameter, the length of the

armature, and the speed. When an alternator is to be designed, the speed S is usually specified, and the value of k_w is known from the type of winding that will likely be used. The values of %, $\mathbf{B}_g$, and K are also fixed within comparatively narrow limits when the style of machine and frequency are known. From formula **5**, Art. **24**,

$$d^2 = \frac{5.48 \times 10^8 \times W}{k_w \, l \, \% \, \mathbf{B}_g K S}$$

or,

$$d = \sqrt{\frac{5.48 \times 10^8 \times W}{k_w \, l \, \% \, \mathbf{B}_g K S}} \qquad (1)$$

From this formula, d can be calculated if l and the other quantities are known. Also,

$$l = \frac{5.48 \times 10^8 \times W}{k_w \, d^2 \, \% \, \mathbf{B}_g K S}, \qquad (2)$$

from which l can be determined when d and the other quantities have been decided on.

In many cases the diameter d is fixed by some of the attendant conditions. For example, the designer may have to make up a machine by using existing field and armature punchings, in which case the approximate length of core l, not including ventilating ducts, can be calculated from formula **2**.

If neither the diameter nor the length are fixed by the conditions, a diameter should be chosen so that the length l will be from .75 to 1.5 times the pole pitch. If the length is much greater than this, the poles become very long (parallel with the shaft) and narrow, thus making the periphery of the pole cores unnecessarily long and requiring a correspondingly increased weight of field copper. Long, narrow poles also have large field leakage. Some generators, for example, turbo-alternators, have the diameter limited by the maximum peripheral speed permissible for the rotor; and if the output is large, long armatures with correspondingly long poles are unavoidable.

26. Output Coefficient.—Formula **5**, Art. **24**, may be separated into two parts, one part to include all those quantities which are subject to wide variation, and the other

part those which are fixed within comparatively narrow limits, as follows:

$$\frac{d^2 l \times S}{W} = \frac{5.48 \times 10^8}{k_w \% \mathbf{B}_g K}$$

or, since $\frac{\text{watts}}{1{,}000}$ = kilowatts (K. W.),

$$\frac{d^2 l \times S}{\text{K. W.}} = \frac{5.48 \times 10^{11}}{k_w \% \mathbf{B}_g K} \qquad (1)$$

The quantity $d^2 l$ (square of diameter in inches times length in inches) is commonly called the *cylindrical inches* of the armature. Since the output is proportional to the speed, it may be expressed as so many kilowatts per revolution. Thus, kilowatts per revolution per minute equals $\frac{\text{K. W.}}{S}$. The left side of formula **1** may be written $\frac{d^2 l}{\frac{\text{K. W.}}{S}}$, and this expresses the *number of cylindrical inches per kilowatt per revolution*. Since, for a given class of machines, the right side of the formula is nearly constant, the cylindrical inches per kilowatt per revolution are also nearly constant.

It is usually more convenient to express this **output coefficient** in terms of the cylindrical inches per kilowatt per 100 revolutions per minute. The number of kilowatts at 1 revolution per minute is $\frac{\text{K. W.}}{S}$, and at 100 revolutions per minute, $\frac{\text{K. W.} \times 100}{S}$; hence, the number of cylindrical inches per kilowatt at 100 revolutions per minute is

$$\frac{d^2 l}{\frac{\text{K. W.} \times 100}{S}} = \frac{d^2 l \times S}{\text{K. W.} \times 100},$$

and, dividing both members of formula **1** by 100, gives

$$\frac{d^2 l \times S}{\text{K. W.} \times 100} = \frac{5.48 \times 10^9}{k_w \% \mathbf{B}_g K} \qquad (2)$$

27. The values of k_w, $\mathbf{B}_g$, and K generally found in alternators have been given previously. The ratio of pole arc

to pole pitch % usually lies between .5 and .7, and in most cases, on revolving-field machines, where the pole tips project more or less to hold the coils in place, the value of % lies between .6 and .7.

If the average values $k_w = .95$, $\% = .625$, $\mathbf{B}_g = 45{,}000$, and $K = 500$ are taken,

$$\frac{d^2 l \times S}{\text{K. W.} \times 100} = \frac{5.48 \times 10^9}{.95 \times .625 \times 45{,}000 \times 500}$$
$$= 410, \text{ approximately}$$

EXAMPLE.—Assuming that the values of k_w, %, $\mathbf{B}_g$, and K are the same as just given, and that the armature core is 90 inches in diameter, how long should be the armature core for an alternator so as to give 250 kilowatts at 200 revolutions per minute?

SOLUTION.—The output coefficient will be 410 cyl. in. per K. W. at 100 R. P. M., as obtained from formula **2**, Art. **26**. Thus, $\frac{d^2 l \times S}{\text{K. W.} \times 100} = 410$; $S = 200$; K. W. $= 250$; and $d = 90$. Hence,

$$90^2 l = \frac{410 \times 250 \times 100}{200},$$

and $$l = \frac{410 \times 250 \times 100}{200 \times 8{,}100} = 6.33, \text{ say } 6\tfrac{3}{8}, \text{ in. Ans.}$$

28. Values of Output Coefficient.—For a given output and speed, formula **2**, Art. **26**, shows that the cylindrical inches, $d^2 l$, which are a measure of the size of the armature, depend on the values of the quantities k_w, %, $\mathbf{B}_g$, and K. The constant k_w cannot be changed much, since it depends merely on the arrangement of the armature coils; the pole arc cannot be made much over two-thirds of the pole pitch without causing a large amount of magnetic leakage and crowding of the field windings; also, $\mathbf{B}_g$ cannot be increased beyond a certain amount for reasons previously given, but the value of the quantity K admits of some variation, and the greater the number of ampere-conductors per inch, the smaller will be the armature. However, if K is made too large, the machine is liable to overheat, and it can only be made high with safety when the ventilation is good.

A machine with a large number of ampere-conductors

per inch, while it has a low output coefficient and may therefore have a small armature, is not necessarily a cheap machine to build, since it must contain a relatively large amount of copper. For ordinary polyphase alternators, the output coefficient (cylindrical inches per kilowatt at 100 revolutions per minute) will usually lie between 250 and 600, the lower limit being for machines operating at high peripheral speed, having usually good ventilation, and designed with a relatively large amount of copper. In single-phase machines, all the armature surface is not utilized, and the output coefficient is considerably larger; in such cases, it usually lies between 500 and 900.

MECHANICAL CONSTRUCTION OF ALTERNATORS

ARMATURE

ARMATURE CONDUCTORS

29. Fig. 24 shows cross-sections of conductors used for alternator **armature coils.** For armature windings having many turns per coil, round, double cotton-covered wire is used. A round wire, (*a*), is more easily handled than wire of square cross-section (*b*), though the square wire utilizes the slot space more effectively and gives a larger cross-section of copper for a fixed slot space. Unless the corners are well rounded, square wire often gives trouble when wound into coils having sharp bends, because the insulation is very liable to become cut through on the corners, resulting in short circuits. In order to reduce the liability of such accidents, square wire used for alternator armature coils is nearly always double cotton-covered.

Armature coils having only one or two turns and intended for large current-carrying capacity are usually made of copper

strip, which may be either taped, cotton-covered, or bare, the adjacent strips of a coil being separated from each other by suitable insulating material; sections of this kind are shown in Fig. 24 (*c*), (*d*), (*e*), and (*f*). If a conductor of large cross-section is required, it is made up of a number of strips or wires in parallel, because if a large, solid bar were used, there would be a loss due to eddy currents in the conductor.

When a conductor is composed of a number of strips or wires in parallel, they should be separated from one another

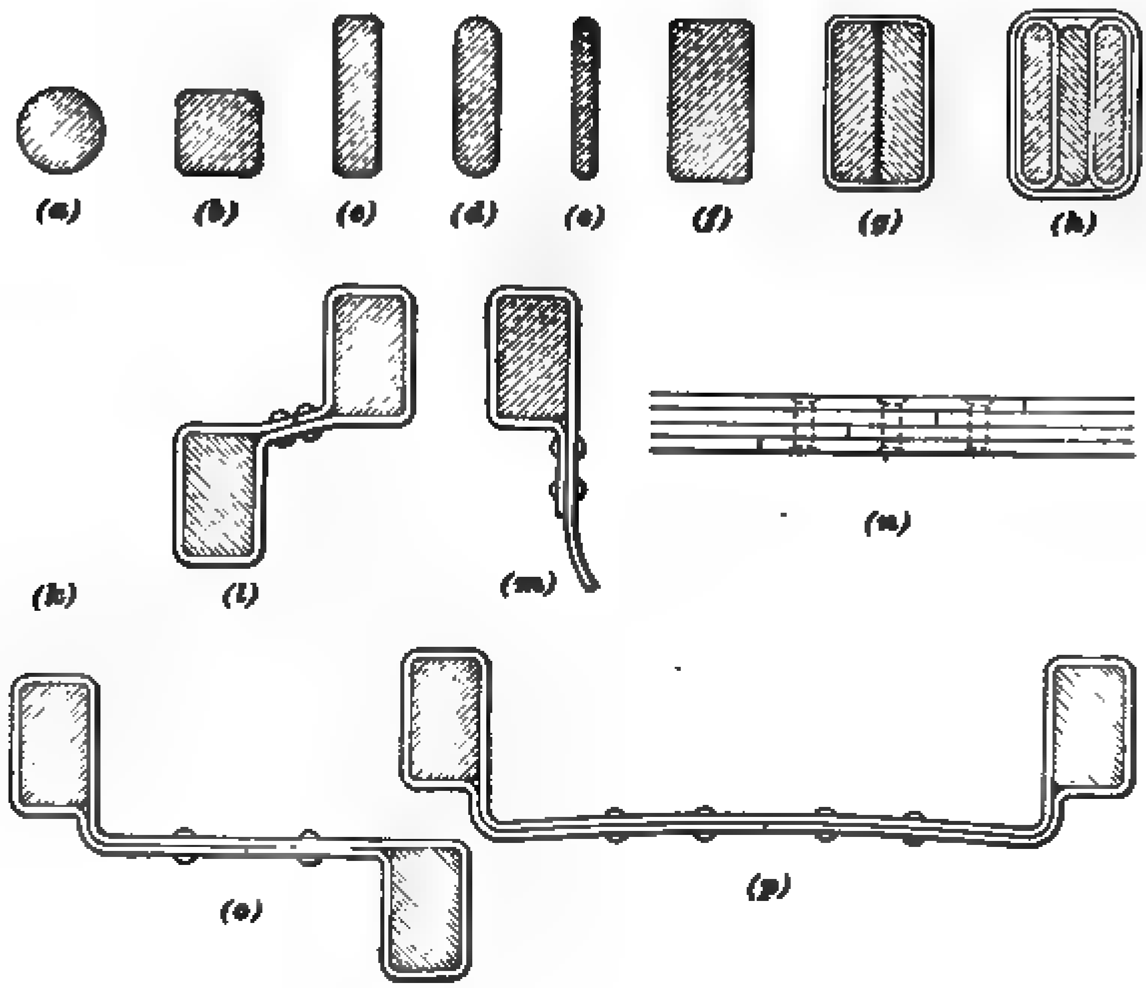


FIG. 24

by light insulation in order to prevent eddy currents; thin paper is sufficient for this purpose. For example, if a conductor (*g*) is composed of two strips in parallel, thin insulation should be placed between them, as shown by the black center line. A coil section having three conductors or three turns, two of them being insulated and the middle one uninsulated, is shown at (*h*).

For rotors designed for induction motors where the frequency of the currents generated in the rotors is usually low, comparatively heavy bars can be used for the conductors without causing an undue eddy-current loss; for example, the bars for a squirrel-cage rotor can be much heavier than would be allowable for conductors on the stator.

30. With bar windings, various forms of connectors are required for joining the conductors or for making connections between the phases. With wire-wound coils, the connections are made by heavily insulated wire or cable, all joints being first carefully bound together with fine copper wire and then soldered and taped.

On high-pressure alternator armatures, the connections between coils must be very carefully insulated; otherwise, when subjected to the high-potential insulation test, breakdowns will occur between the coil connections and the frame of the machine.

Some of the forms of connectors used with bar windings are shown in Fig. 24 (*k*), (*l*), (*m*), (*o*), and (*p*). At (*n*) is shown a method of joining conductors made up of a number of strips in parallel; the strips are cut off at unequal lengths, and after having been fastened firmly by rivets, are sweated together with solder. The clip (*k*) is used for joining the ends of bars that come directly above each other. The diagonal connector (*l*) is used for joining an upper conductor to one diagonally below it, as for example at *a* in the winding shown in Fig. 19. The conductor (*o*) is used for making joints, as indicated at *b*, Fig. 19, and the long connector (*p*), for joining the ends of bars, as at *c*, Fig. 19.

ARMATURE CORE AND YOKE

31. Armature Slots.—The general practice in America is to use **open armature slots** wherever possible, but partly closed slots are now used much more than formerly. In Fig. 25 (*a*), (*b*), (*e*), (*f*), (*m*), (*p*), and (*q*) are shown

typical forms of open slots, (*a*), (*b*), and (*e*) being the kinds most commonly used for alternators. The deeper and narrower slots (*f*), (*p*), and (*q*) are used for induction motors, (*f*) being used for rotors having the conductors held in place by band wires.

For stator windings with open slots, it is necessary to provide means for holding the coils in place, and this is

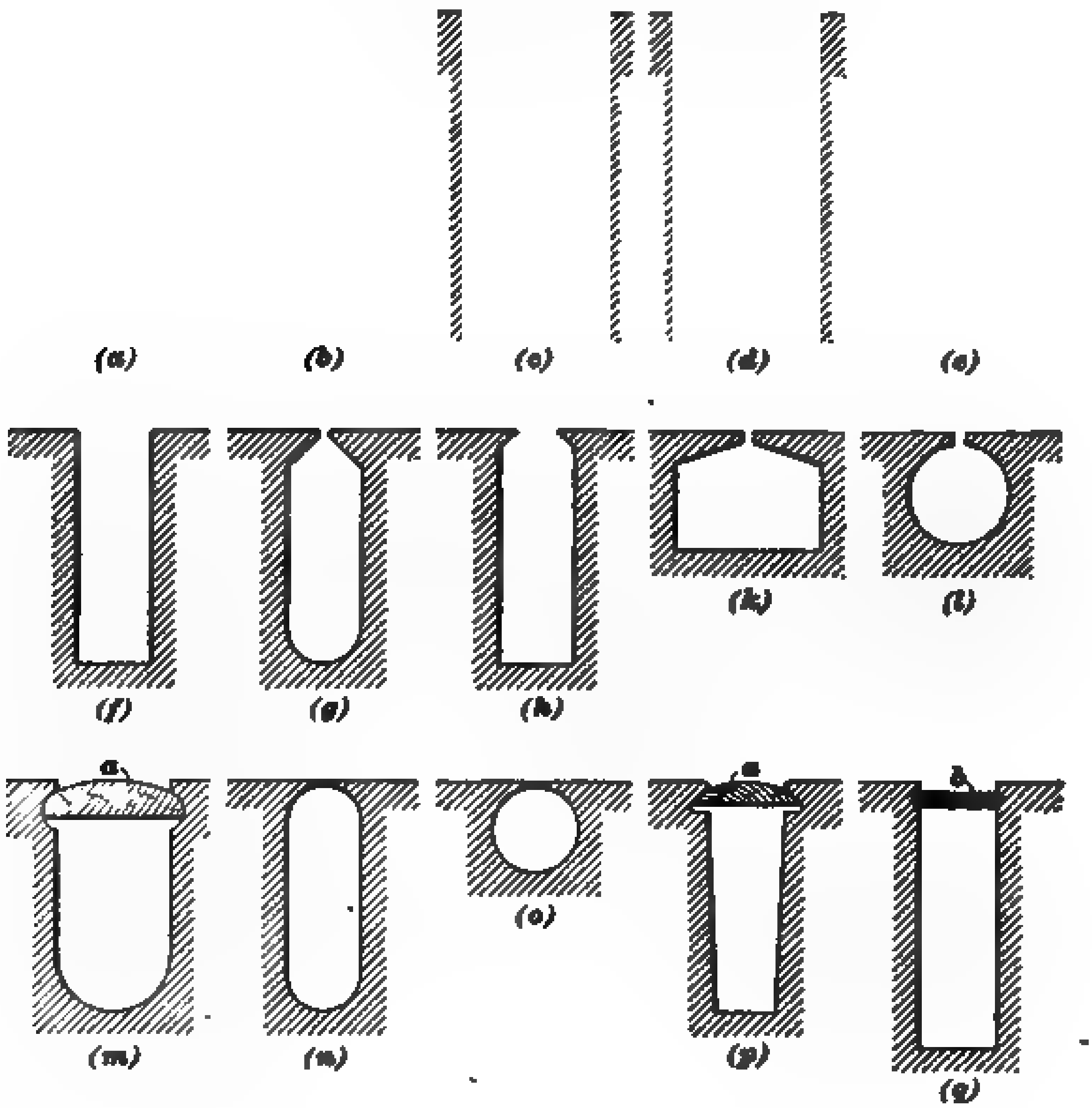


FIG. 25

usually done by wooden wedges *a*, or fiber wedges *b* held in nicks at the top of the slots. Very narrow, deep slots should be avoided, as they give rise to large leakage across the top of the slots, thus making the inductance of the armature windings high. The open slot shown at (*p*) is

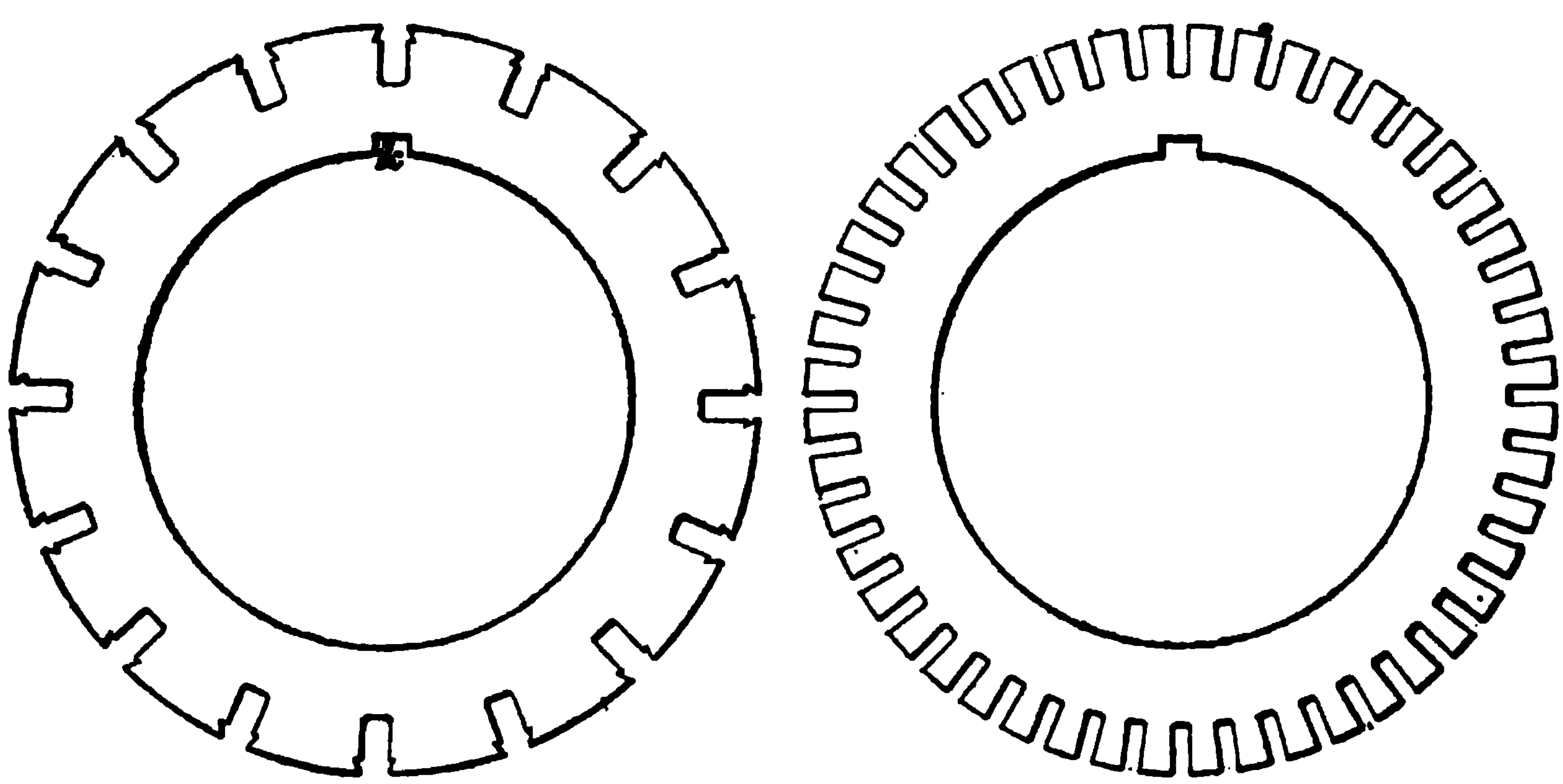
slightly wider at the top than at the bottom, thus making it easier to place the coils in position. In nearly all cases, however, the slots are made with straight sides. The chief advantage of open slots is that they permit the use of form-wound coils, which can be made up complete and then placed in the slots. Such coils make the cost of winding comparatively low, and the coils may be thoroughly well insulated.

32. The most common forms of **partly closed slots** used for alternator armatures are shown in Fig. 25 (*c*), (*d*), (*g*), and (*h*). On bar-wound armatures, the bars can be easily pushed endwise through the slots; and as there are only a few conductors per slot, it is a comparatively easy matter to make the end connections. With wire-wound coils having many turns, the conductors of a coil can either be threaded one at a time endwise through the slots by hand, or they can be wound on a form, then one end cut, and the two sides of the coil straightened out. The sides can then be pushed endwise through the slots and the projecting ends formed to shape and joined together again. Each conductor must be joined to the corresponding one in the other part of the coil, so as to make the turns complete; however, if there are many turns, this is a rather costly process. With a given magnetic flux, the use of partly closed slots makes the magnetic density in the air gap lower, or with a given density and magnetizing force, such slots permit the use of a larger flux. A material reduction in the size of armature for a given output can thus be made, and this may counterbalance the increased cost of winding. Another advantage of partly closed slots is that they avoid eddy currents in the pole pieces due to variations in flux across the pole; the armature presents a nearly smooth surface to the pole, and the distribution of flux is practically uniform. A good example of a bar winding with partly closed slots is shown in Fig. 5.

The slots are very seldom totally closed as in Fig. 25 (*n*), though this style has been used for induction motors by a number of European builders. It is better to have a small

opening at the top, in order to prevent the armature current from setting up a large local flux around the conductors. The three styles of slots shown at (*k*), (*l*), and (*o*), are used for the rotors of squirrel-cage induction motors. In all except small motors, the rotor bars are rectangular in cross-section, and the slot shown at (*k*) is the style generally employed. The use of slots (*l*) and (*o*) is confined to small motors with rotor bars of circular cross-section.

33. Armature Punchings.—In the older forms of alternators having rotating armatures, the laminations took the form of the disks shown in Fig. 26 unless the diameter

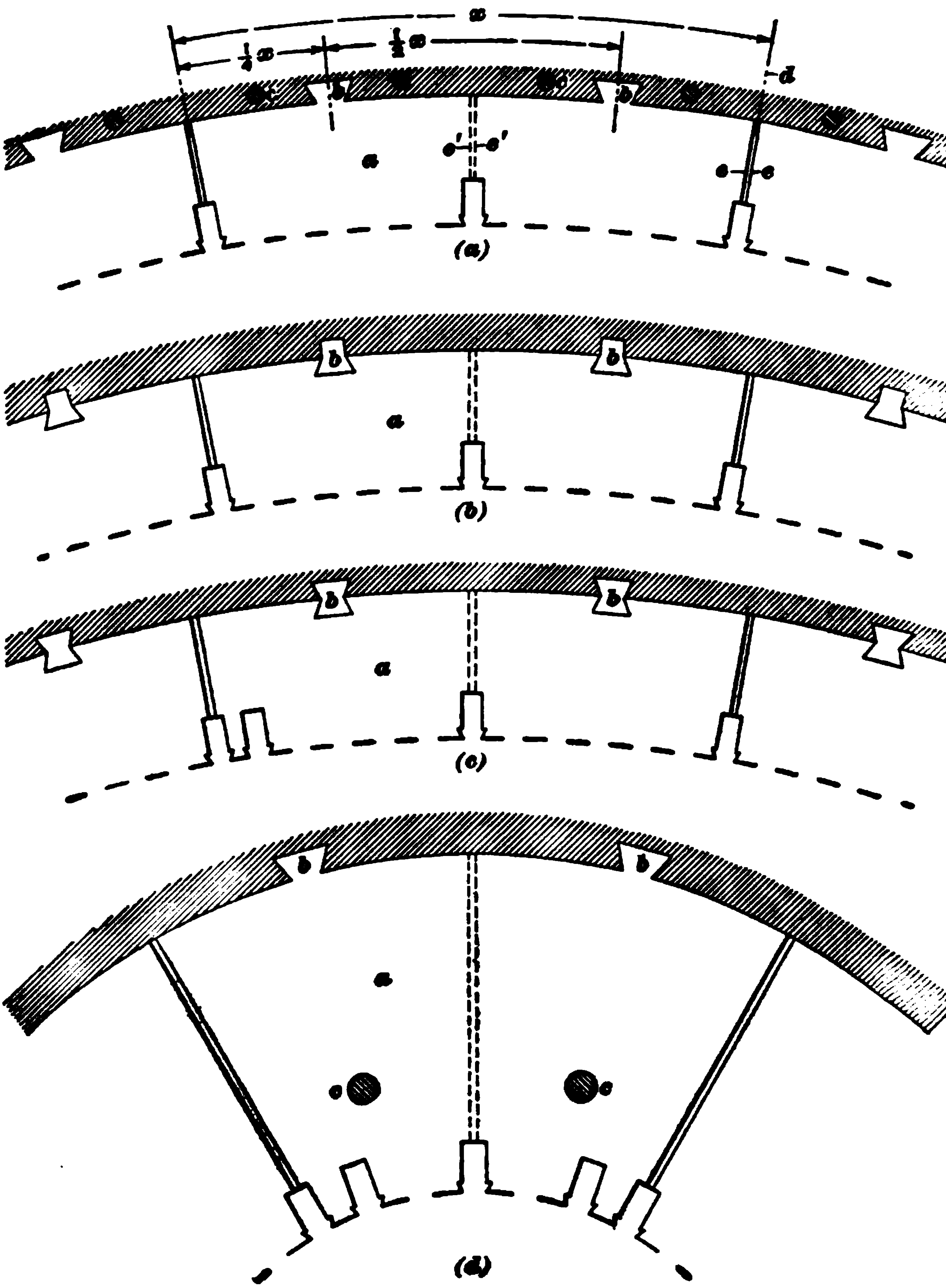


(*a*) (*b*)

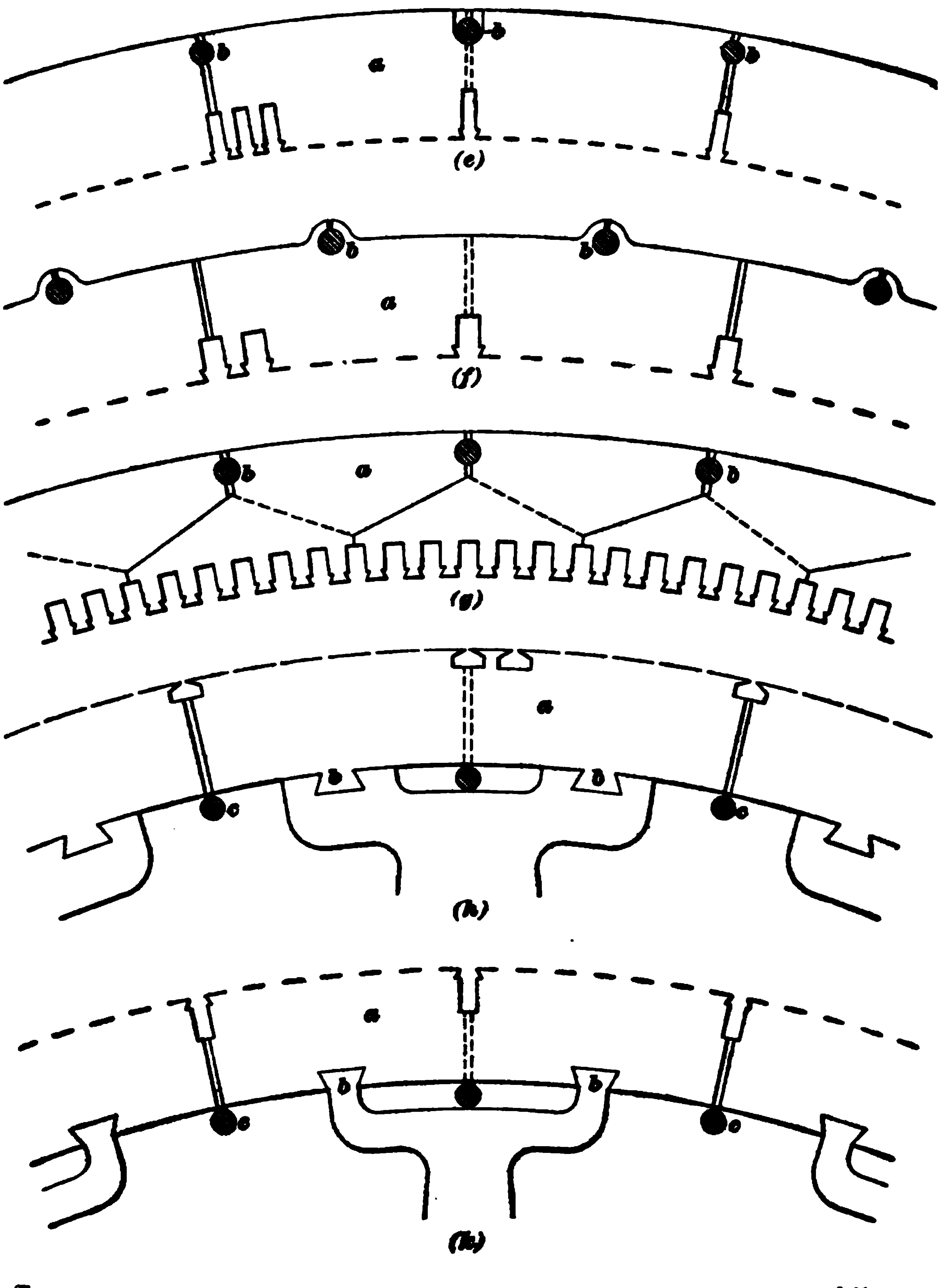
Fig. 26

was large, in which case several segments were used to make up a complete ring. Disks of this form are now little used for alternators, but the same style with different slots is found in rotors for induction motors. In Fig. 26 (*a*), the slots have nicks for retaining wedges, while at (*b*) the slots are straight, thus requiring band wires for holding the coils in place. A keyway *k* receives the key for preventing motion between the disks and their supporting spider.

34. In Fig. 27 are shown several schemes for holding segmental punchings. The number of segments *a* into which a ring is divided must be chosen with reference to the number of slots and the length of punching that can be made



45B



b
a
(e)
(f)
(g)
(h)
c
(k)

with available tools. Long dies are expensive, and their use is avoided as much as possible. The number of slots must be divisible by the number of segments. The supporting bolts or dovetails *b* must be arranged so that each successive layer of punchings can be lapped over the preceding layer, thus breaking joints and providing a continuous path for the magnetic flux. In Fig. 27, only a sufficient number of slots are drawn, in order to show the relation of the dovetails or supporting bolts to the slots.

In the section of core shown at (*a*), the segments *a* are held in place by dovetail projections *b*, which fit into corresponding slots milled in the cast-iron supporting yoke. Each lamination has two dovetail projections. The ends of the punchings are cut a little less than the full arc *x*, so that there will be a clearance of about .02 inch between abutting ends *e*, *e*, thus making the stampings go into place more easily. The next layer of stampings is put on so that the joints come midway between the joints of the first layer, as shown at $e'e'$; thus, the joints of no two adjacent layers are in line with each other. The dividing line between punchings must come at the center of a slot or tooth; it is nearly always made to come at the center of a slot.

Two other kinds of dovetail supports are shown at (*b*) and (*c*). Dovetail pieces *b* are fastened to the frame, and corresponding notches are punched in the laminations. About the only advantage of this construction is that it saves sheet iron, because the width of the metal sheet from which the punching is made is reduced by the amount that the dovetail projects on the type shown at (*a*).

35. In ordinary alternators, the depth of iron under the slots is not large, and the laminations can be firmly held by end plates secured with bolts *c*, Fig. 27 (*a*), that pass through the supporting yoke behind the core; thus, no bolts pass through the stampings. In large turbo-alternators that have only a few poles with a very large flux per pole, the radial depth of iron between the slots and the supporting yoke becomes unusually great, the punchings taking the form

shown in Fig. 27 (*d*). It is thus frequently necessary to pass clamping bolts *c* through the core, in addition to those passing behind it, in order to hold the inner part of the laminations securely. These bolts must be carefully insulated from the core and also from the end clamping plates. The bolts through the core are cut by the magnetic flux and become a seat of electromotive force, and if they are not insulated, they will, in conjunction with the core or frame, form a closed circuit in which heavy currents will circulate.

36. In the cores shown in Fig. 27 (*e*), (*f*), and (*g*), the laminations are supported on bolts *b*, located at the rear edge of the punchings, where the magnetic flux has little effect; the bolts may therefore be only lightly insulated without danger of stray currents. For armatures of moderate diameter, the bolt support is satisfactory and is considerably cheaper than dovetails. This method of support also has the advantage that the number of bolts can be readily changed to suit different numbers of slots and segments without requiring any change in the casting for the supporting yoke. With dovetails, a change in the number of slots frequently requires a change in the number of segments and the location of the dovetails, thus necessitating a change in the number of ribs in the casting in which the dovetail grooves are milled. This makes it necessary to change the pattern for the yoke, in addition to making a new die for punching the segments. The form of lamination shown at (*g*) is interesting, the ends of the segments being cut on the slant, as shown by the full lines. When the core is assembled, the laminations in successive layers are reversed, thus giving a long lap joint.

For rotating armatures or for induction-motor rotors of large diameter, the constructions shown in Fig. 27 (*h*) and (*k*), are suitable. At (*h*), the dovetail projections are on the laminations, while at (*k*) they are on the spider arms. The method shown at (*k*) is to be preferred, as it is stronger than (*h*) and effects a saving in iron. In both cases, the clamping bolts *c* through the end plates pass beneath the core.

37. Thickness of Iron.—The iron used for building up the cores for alternating-current apparatus is usually from 12 to 18 mils (.012 to .018 inch) thick. Thicker iron can be used for revolving-field punchings, but for iron cores subjected to alternating flux, unless the frequency is very low, it is not advisable to use iron much thicker than 18 mils.

38. Armature Spiders.—In an alternator having a revolving armature, the armature punchings are supported on a suitable spider and clamped between end plates, in much the same way as described for direct-current machines. The rotor punchings for induction motors are mounted in the same manner. Fig. 28 shows a form of spider suitable for

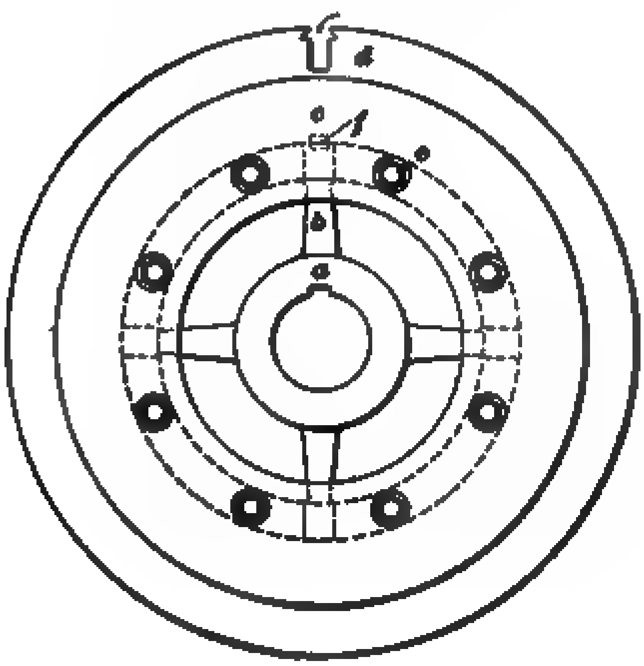


FIG. 28

a revolving armature having a chain winding of heavy coils, in which the coil ends where they project beyond the core are self-supporting. The spider consists of a hub *a* with four projecting arms *b*, all cast in one piece. The hub is provided with a keyway for keying it to the shaft. The laminations *d* are clamped between the end plates *c* by bolts *e*, which pass under the core; d_a is the external diameter of the armature, and l_a the spread of the laminations, including four air ducts, which are formed by inserting space blocks between the

laminations, as described in connection with the design of direct-current machines. A key *f* prevents the punchings from turning on the spider.

The spider shown in Fig. 29 has projecting flanges *a* on the end plates, in order to support the rotor bars or coils when they are not stiff enough to be self-supporting. The end connections are bound down securely by means of band wires, and the ventilating openings *b* allow free circulation of air. The recesses *c* in the rim are provided for balancing the rotor after it has been wound; molten lead is poured into these holes, which, on account of their dovetail shape, hold the lead in place.

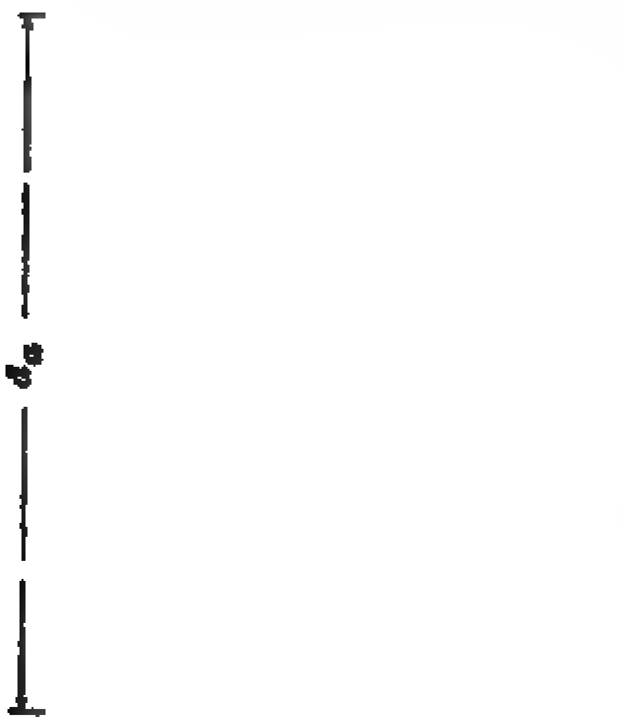


Fig. 29

Fig. 30 shows a spider for a rotor of large diameter. Dovetails are cut in the ends of the arms *r*, and the laminations are held as shown in Fig. 27 (*h*). Spiders should always be designed to allow free circulation of air through the rotor ventilating ducts. In many cases, particularly in small machines, the spokes of the spider are shaped so as to act like fan blades and thus force air through the ducts and around the end connections of the winding.

39. Stator Yokes.—When the armature is stationary, a suitable yoke or frame must be provided for holding the punchings. Fig. 31 shows an **armature yoke** for a large revolving-field alternator. When the diameter is large, the yoke is made in halves *A* and *B*, the two parts being securely bolted together and held in line by square splines. The yoke is supported on feet *a*, *a*. The dovetail grooves *c* hold the armature laminations *d* in place, and these laminations are

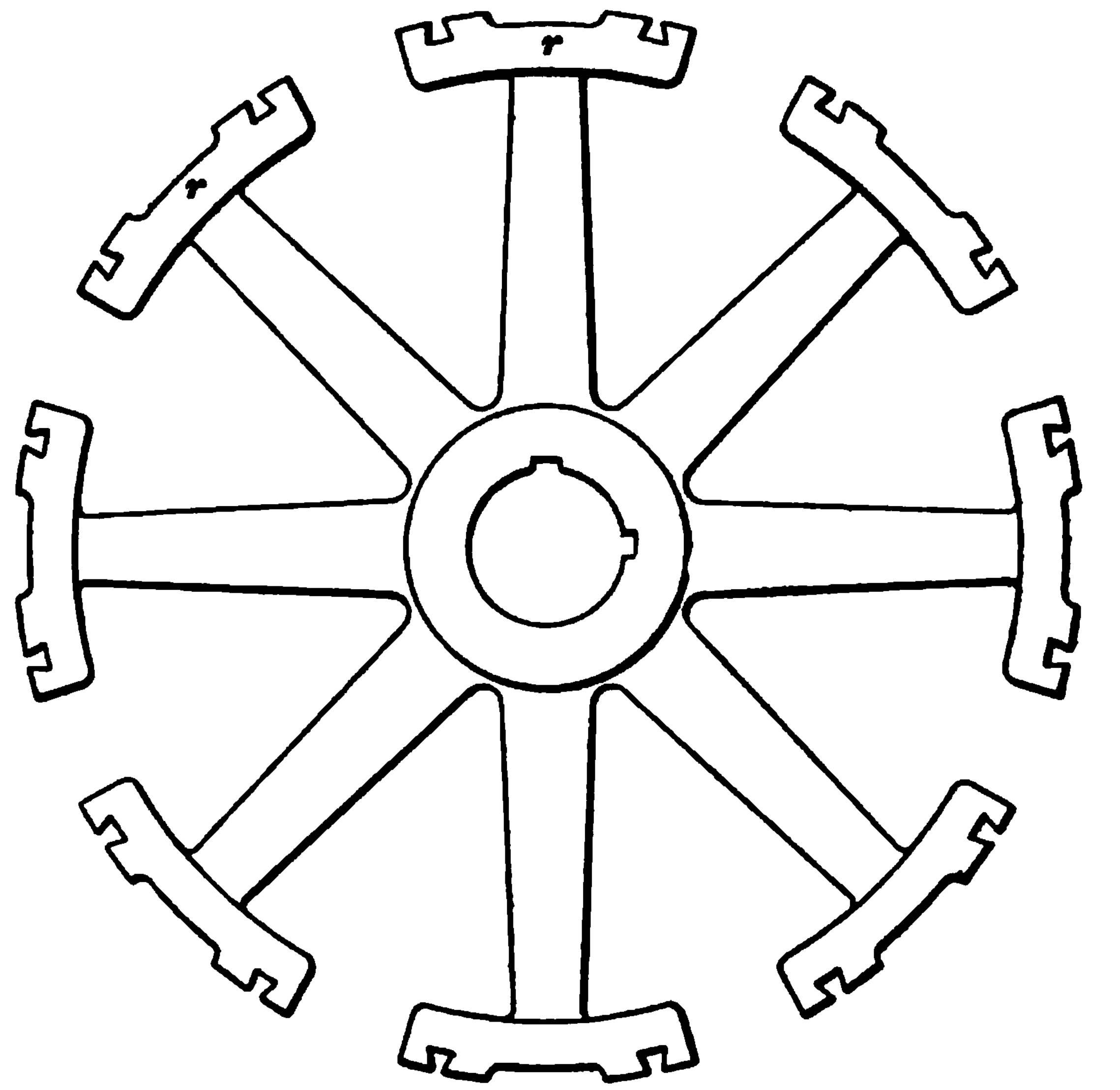


FIG. 30

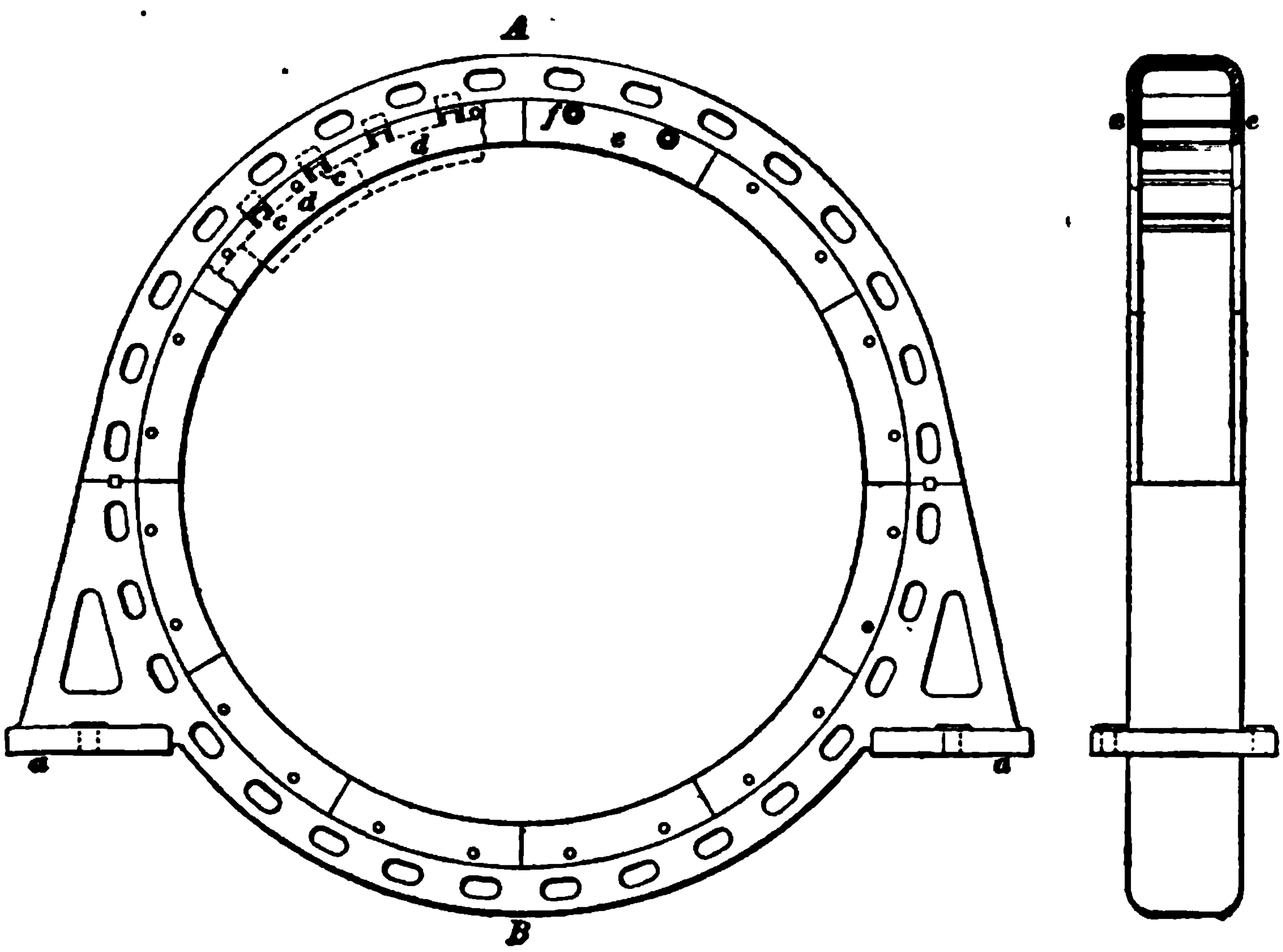


FIG. 31

clamped between end plates *e*, which are held by bolts *f*. Since the stator yoke serves merely as a support for the core, it should be made as light as possible, but under no condition should it be made so light as to lack the necessary stiffness. With machines of small diameter, there is no difficulty in securing ample stiffness with a comparatively light yoke, but with large engine-type alternators, in which the armature diameter is frequently from 10 to 20 feet, the yoke must be made deep and heavy, or there will be danger of the stator sagging and getting out of center with the revolving wheel.

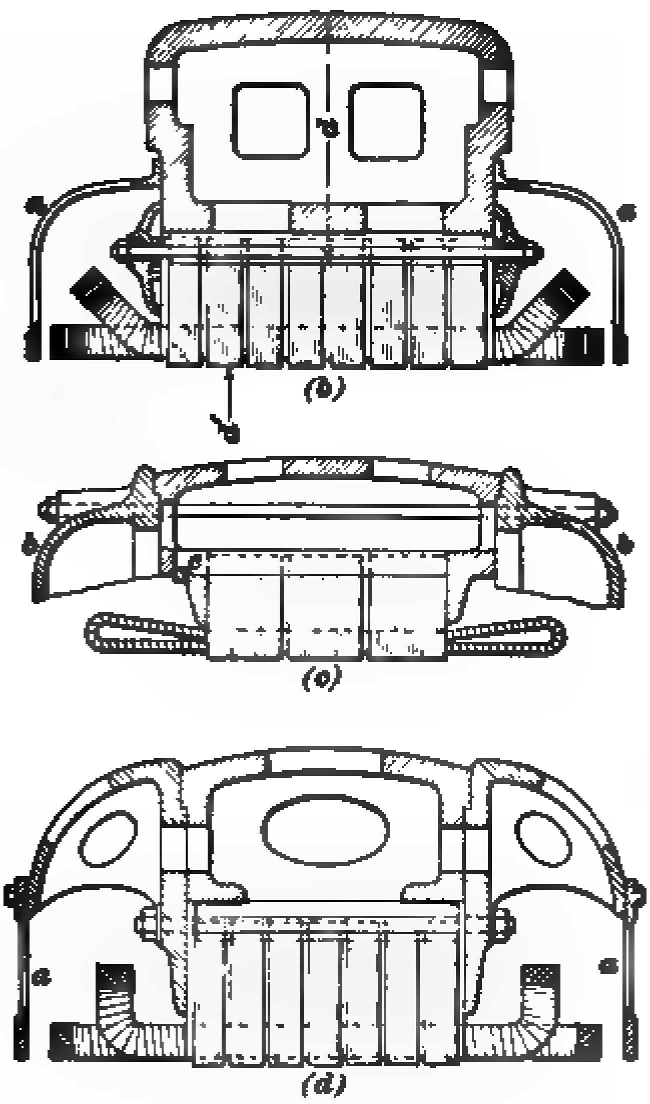


Fig. 32

Usually, the yoke is of the box-frame type of construction, some common forms of which are shown in Fig. 32. At (*a*), the laminations are supported on bolts; one end head is cast with the main part of the yoke, and the other is cast in segmental sections. In the form shown at (*b*), the dovetail slots for the stampings have to be milled out. A head cast on one side of the yoke would

interfere with the machine work; hence, it is necessary to have both heads or clamping plates separate. In box-frame yokes for alternators of large diameter, the depth *d*, measured from the outside diameter of the dovetails to the outside of the yoke, should be from $\frac{1}{8}$ to $\frac{1}{10}$ the diameter *d'* of the armature, in order to secure the requisite stiffness. The light-winding shields *a*, *a* are cast in segments and bolted to the yoke; they protect the ends of the coils and should be made as open as possible, in order not to interfere with the ventilation.

The yoke shown in (*c*) is especially suitable for small alternators or induction motors where the bearings are carried in end housings *b*, *b* bolted to the stator yoke. In this case, the punchings are made in one piece, and are clamped between one end head cast with the yoke and another movable head that is pressed into place and held by a split ring *c*, against which the movable head backs up when the pressure is removed.

Fig. 32 (*d*) shows a form of yoke in which the end heads are designed to reinforce the yoke and stiffen it so that a smaller depth of yoke can be used. The end heads continue out over the end connections of the windings in the form of shields, or heavy flanges. As the shields are bolted firmly to the central part of the yoke, they help materially in supporting the core.

40. In all these constructions, the yoke is provided with numerous openings, so that there is no interference with the free circulation of air around the core and windings. Fig. 33 shows a typical stator with box-frame yoke and two-layer winding. A few coils have been removed at the dividing line *a a*, so that the top half can be lifted off. The open winding shields are shown at *b*, the head of one of the bolts for holding the upper and lower halves of the yoke together at *c*, and the terminals of the winding at *t*. This armature is 12 feet 6 inches in diameter.

41. Fig. 34 shows a recent design of yoke known as the *skeleton type*, in which the weight of metal has been cut down

Fig. 33

to the lowest possible amount. This yoke consists merely of deep flanges *a*, *a* connected by cross-ribs *b*; except where covered by the ribs, the laminations are exposed to view.

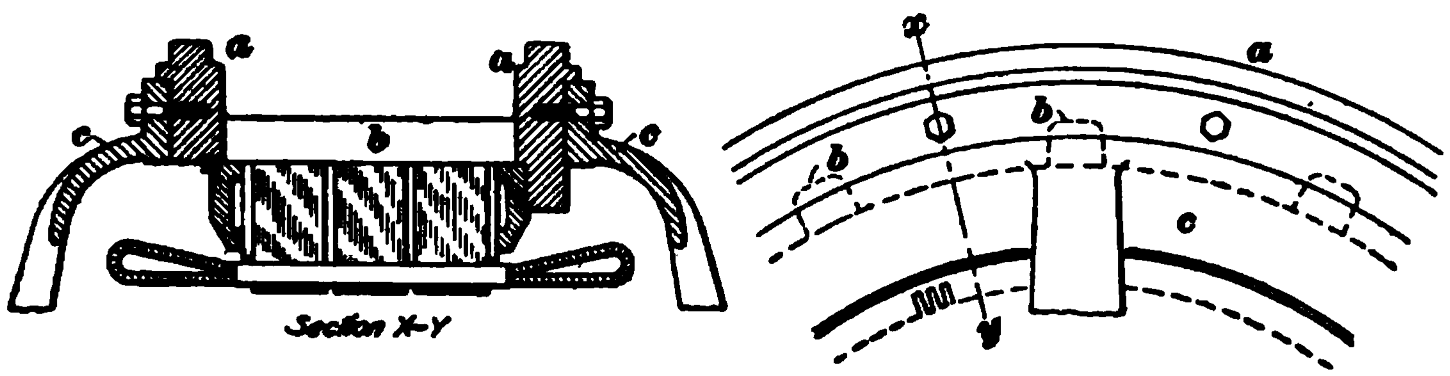


Fig. 34

The bearings are carried in end shields *c* bolted to the frame. This type of yoke is not very handsome in appearance, but it is light and offers very little obstruction to ventilation.

REVOLVING FIELDS

42. The construction of a **revolving field** depends considerably on its diameter and on the speed at which it must run. In slow-running engine-type alternators, a cast-iron spider with pole pieces bolted to or dovetailed into the rim is amply strong. In waterwheel machines and others, where the peripheral speeds are from 6,000 to 8,000 feet per minute, the spider may be made of cast steel. For still higher peripheral speeds—8,000 to 10,000 feet per minute—a laminated rim mounted on a cast-iron or steel spider may be required, and for speeds above 10,000, as in turbo-alternators, a special rotor construction must be used throughout.

43. Construction of Poles.—Except for certain types of turbo-alternators, the general practice is to make the pole pieces laminated rather than solid. This prevents eddy currents in the pole faces due to inequalities in the flux caused by the armature teeth. In turbo-alternators, the air gap between armature and field is usually so large that solid poles can be used without any great eddy-current loss, and it is often advantageous to use a solid-pole construction. Fig. 35 shows a typical laminated pole piece for an engine-type alternator, in which the poles are comparatively small and

numerous. The stampings *a* are held between the end plates *b* by means of countersunk rivets *c*. The dovetail-shaped part *d* fits into a groove in the spider rim, and the whole pole with its field coil is secured by steel keys driven in alongside the dovetail.

FIG. 35

Fig. 36 shows part of a field spider with a dovetailed pole. The pole is held by two tapered steel keys *a* driven in as shown, and the strip-wound exciting coil is held between the projection *b* on the end plates of the poles and the ring *c*,

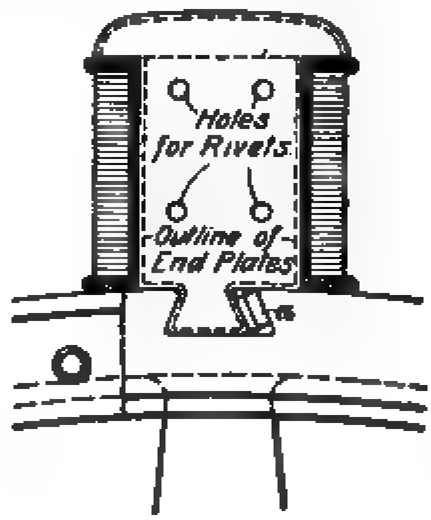


FIG. 36

which forms a seat for the coil projection and also covers the dovetail slots.

Fig. 37 shows a solid pole piece (*a*) together with its strip-wound coil (*b*), which is pulled apart to show the method of winding. Practically all exciting coils on revolving fields are now made of copper strip wound on edge. Successive layers are separated by tough insulating paper, which is held

in place by insulating varnish that is thoroughly baked in. Round-wire winding is not suitable for these coils, because the heavy pressure to which the insulation is subjected on account of centrifugal force would cause the insulation to be cut through.

44. Fig. 38 shows the usual method of attaching laminated poles to the spider by means of bolts. An opening is

Fig. 37

punched in each lamination, and when the pole is assembled and these openings are in line, an iron bar *a* is inserted; bolts *b* are tapped into this bar and secured by spring lock washers *c*. In the bolted construction, the contact surface at the joint *d* between the pole and the yoke is not so large as

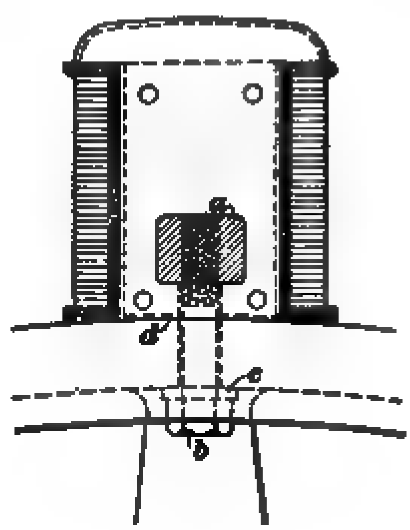


Fig. 38

in the dovetail construction shown in Fig. 36; hence, when laminated poles are attached to a cast-iron spider, the dovetail construction is more desirable, because the flux in passing

from the poles to the spider can spread out more. If the spider rim is made of steel, the increased contact surface is not so essential, because the flux density in steel can be higher. The bolted construction is not generally considered so strong as the dovetailed construction, since there is more likelihood of the poles working loose, but it is cheaper and quite extensively used.

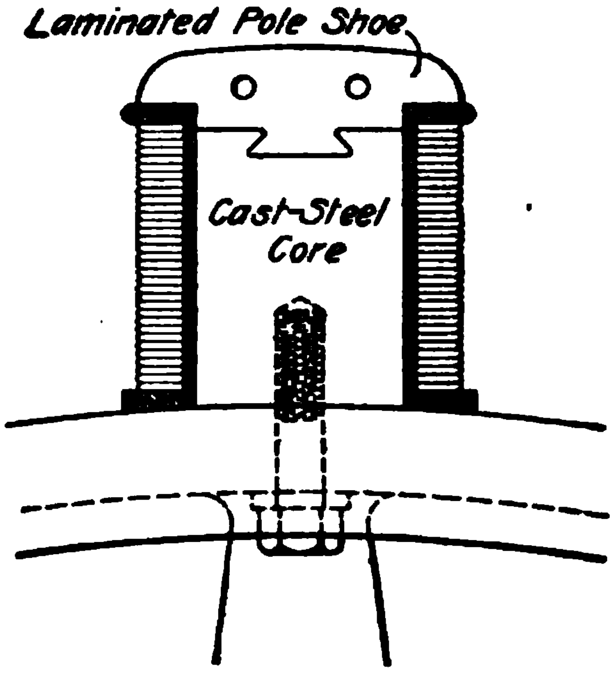


FIG. 39

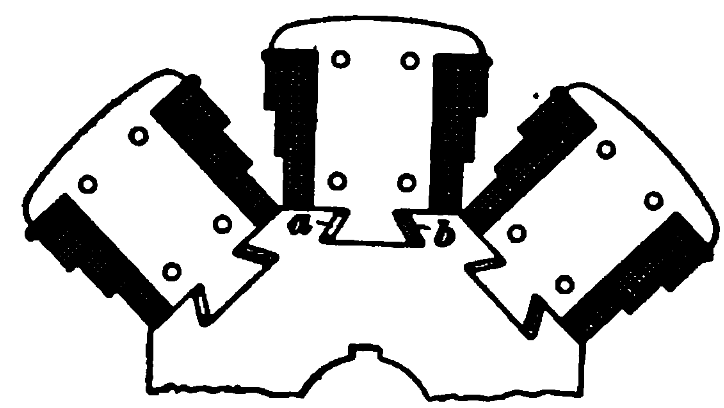


FIG. 40

Fig. 39 shows a pole in which a laminated shoe is combined with a cast-steel core bolted to the rim. The laminated pole prevents eddy currents in the pole face, and the cast-steel core is easily drilled and tapped for the holding bolts.

In Fig. 40 is shown a revolving-field construction frequently used for machines of small diameter. The spider is so small that it can be made up of punchings mounted directly on the shaft. Grooves for holding the poles are provided in the punchings, and since both the spider and the poles are laminated, a shim *a* should be placed between the dovetail and the spider, so as to provide

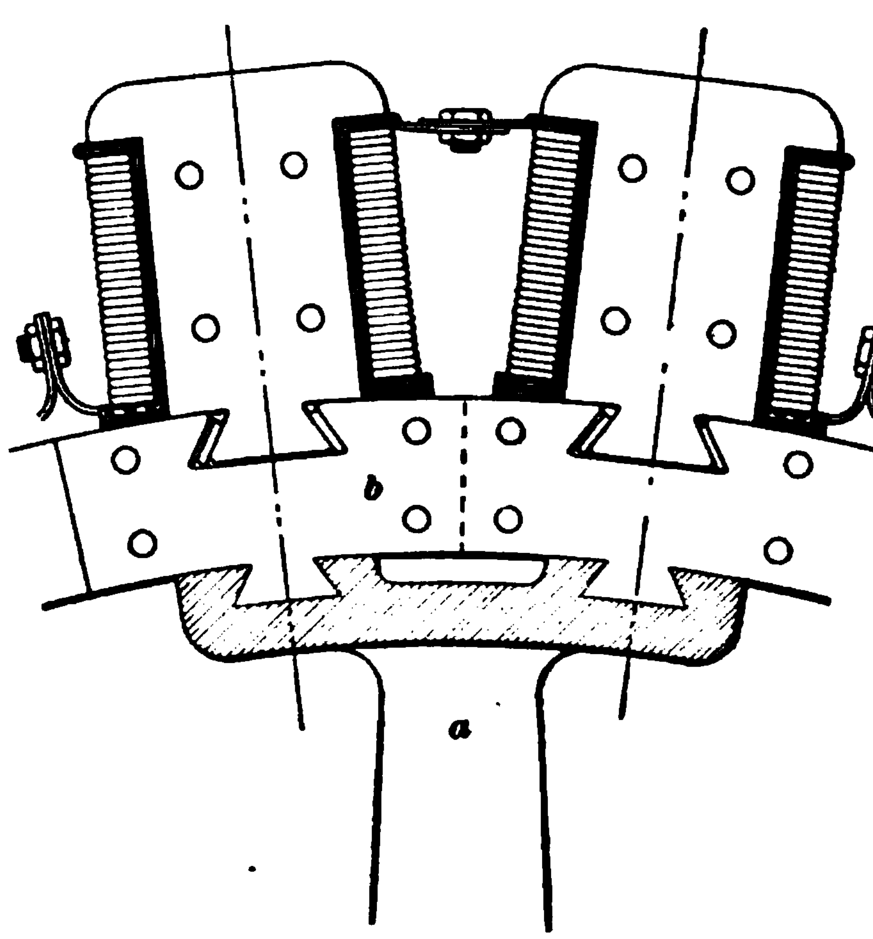


FIG. 41

a good surface against which to wedge the pole when keys *b* are driven into place.

45. Figs. 41 and 42 illustrate two forms of revolving fields, in which both the rim and the pole pieces are laminated. In Fig. 41, the spider arm *a* supports the rim punchings *b*, which are clamped between cast-steel end plates by means of bolts or rivets. The pole pieces are dovetailed to the rim, as shown, thus making a construction suitable for high peripheral speed. In Fig. 42, the laminations *b* make up the poles as well as the rim. The poles are necessarily straight, and the coils are held in place by a cast-copper or brass piece *c*. This casting between the poles also acts as a damper and prevents periodic variations in speed when the alternator is run in parallel with other units. A rim built up of laminations with staggered joints, the whole being securely riveted together, is much stronger than

Fig. 42

Fig. 43

a cast rim, and is in itself capable of resisting large centrifugal stresses. The spider arms serve to drive the rim, and are subjected to much smaller centrifugal stresses than they would be if the rim were cast steel or cast iron.

Fig. 43 shows a sectional view of a machine having a field similar to that illustrated in Fig. 42. The armature laminations *a* are supported by the yoke *b* and are held between the end plates *c*. The coils *d* form a chain winding and are protected by shields *e*, *e*. The field punchings *f* are bolted between end plates *g* and keyed to spider *h*. The strip-wound coil *k* is held in place by projections on the end plates, and also by castings between the poles, similar to *c*, Fig. 42.

FIELDS FOR TURBO-ALTERNATORS

46. Construction.—In alternators designed for direct connection to steam turbines, the peripheral speed is very high, being usually from 10,000 to 15,000 feet per minute. Special care must therefore be taken in the construction of the revolving field, or rotor, to secure accurate balancing and great strength. While **turbo-alternators** are small for their output, because of the high speed at which they run, the great care and high grade of workmanship necessary in their construction may make their cost as great, or possibly greater, than that of machines of corresponding output designed for lower speed.

47. Figs. 44 and 45 show two forms of fields for alternators direct-connected to steam turbines of the Parsons type, Fig. 44 being a two-pole and Fig. 45 a four-pole field. In each case, the field core is made of thick, forged-steel pieces *a*, with slots milled in them to receive the field coils *b*, which are wound with copper strip. The coils are thus completely bedded in the mass of the steel forming the core, and they are securely retained by bronze wedges *c* and *d*, which are driven into grooves at the top of the slots on the sides and ends of the core and turned off flush with the core surface. Holes *e* are drilled near the shaft to admit air, which

is drawn in through these openings and passes out radially through ventilating ducts provided at intervals in the core.

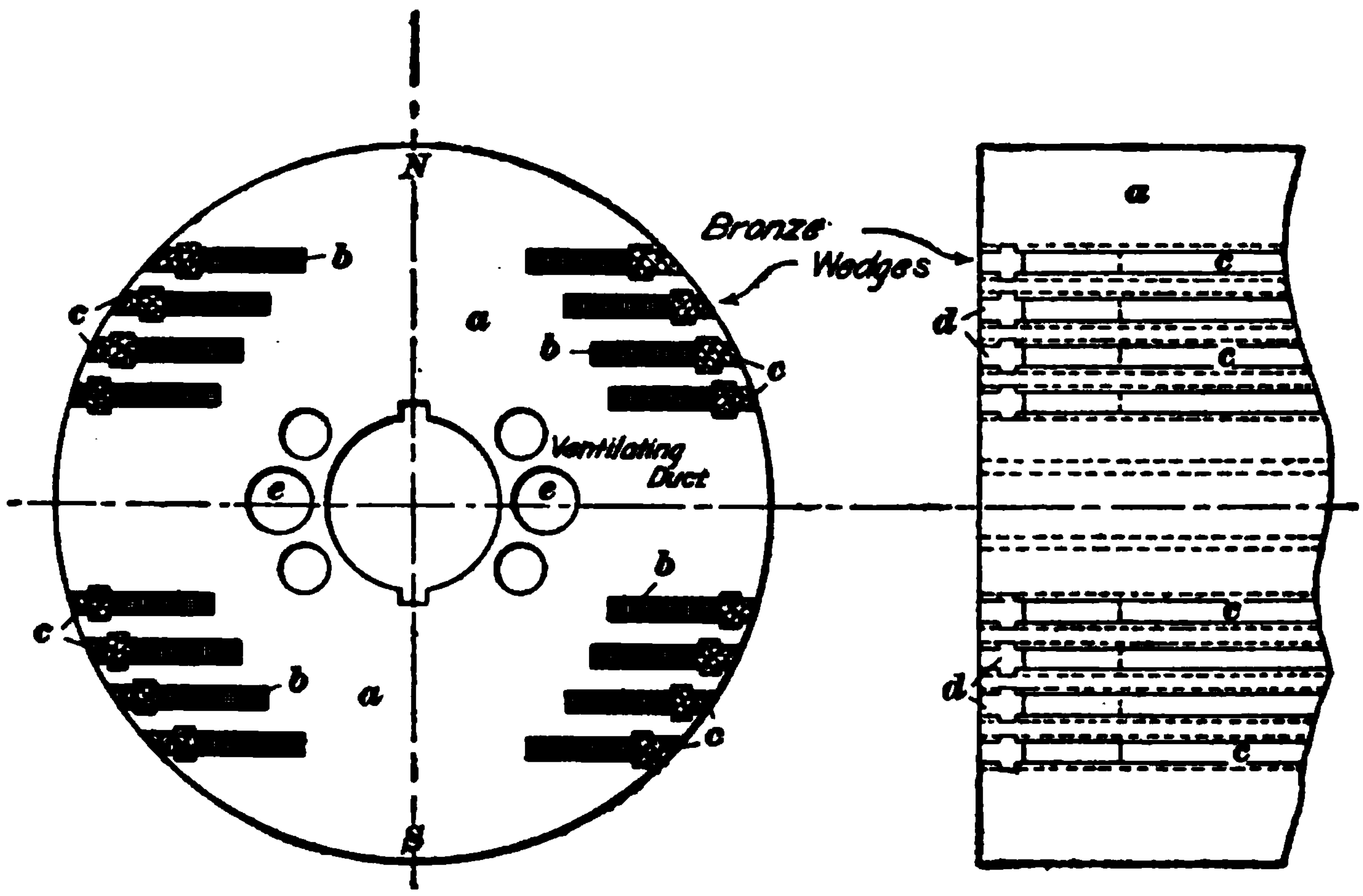


FIG. 44

48. Fig. 46 shows a partly wound Westinghouse two-pole rotor of the same general construction as that shown in Fig. 44.

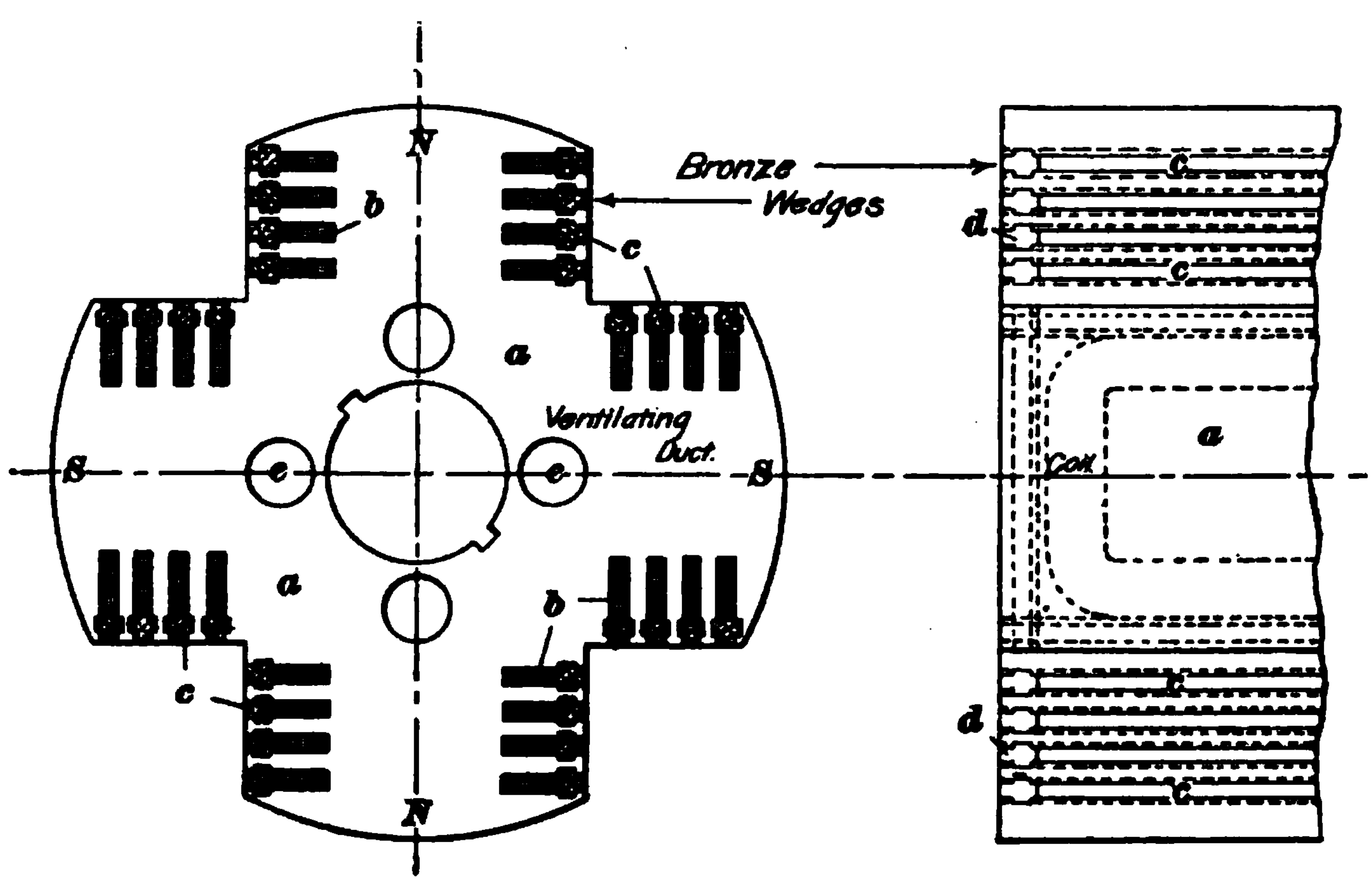


FIG. 45

Insulation is placed in the deep slots, in which the field coils, composed of copper strip, are then wound. The grooves for

the retaining wedges parallel with the shaft are shown at *a*, Fig. 46, while the grooves for the wedges running across the core are shown at *b*. The ventilating holes and ducts are shown at *c* and *d*. The end of the shaft that connects to the steam turbine is necessarily much larger than the end of the shaft that runs in the outer bearing, since the former shaft is subjected to greater stresses.

Fig. 47 shows a complete Westinghouse four-pole rotor, the construction of which is shown more in detail in Fig. 45.

Fig. 47

49. Fig. 48 shows a four-pole rotor for an Allis-Chalmers turbo-generator rated at 1,500 kilowatts at 1,800 revolutions per minute. The steel punchings *a* are provided with radial slots for holding the field coils, which are wound with copper strip. The retaining wedges are shown at *c*, and the ventilating holes and ducts at *d* and *g*. The projecting ends of

the coils are protected by bronze end plates and nickel-steel rings *l*. One of the slip rings *h* for carrying exciting current to the field winding is located at one end of the rotor, and another similar ring at the other end.

Fig. 48

50. Fig. 49 shows one form of turbo-alternator field used with a Curtis steam turbine running at a somewhat lower rotative speed than the Parsons type. The central part *a* is

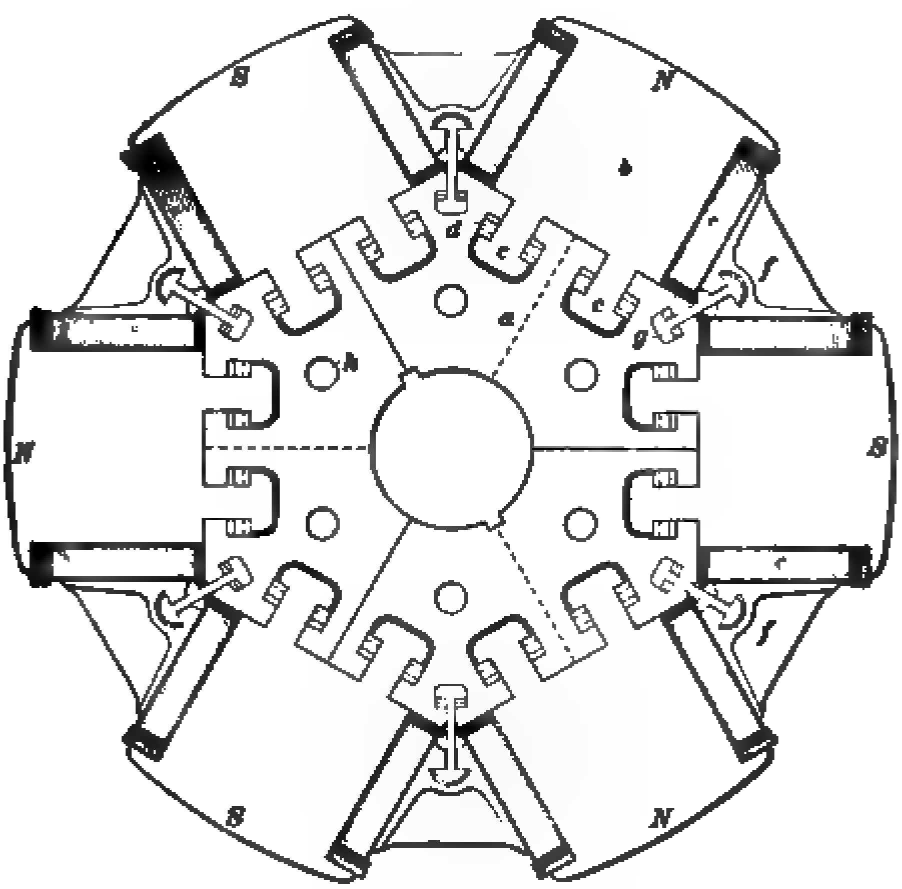


Fig. 49

made of heavy punchings, which are securely held together by large rivets *h*. The poles *b* are secured by T-shaped

projections *c* that fit into slots in the central core and are wedged in place by driving in long keys *d*. To prevent the field windings *e* from bulging out, because of the great centrifugal force, castings *f* are wedged between the coils by links *g*, which are also keyed in place.

51. Another form of turbo-alternator field used with a Curtis steam turbine is shown in process of construction in Fig. 50. The field is part of a four-pole 5,000-kilowatt machine made by the General Electric Company. The rated speed of the field is 750 revolutions per minute. The inner portion of the core *a* is built up of steel discs and is

Fig. 50

provided with ventilating ducts *b* and dovetail grooves *c*. The outer portion of the core is built up of a large number of laminated-iron blocks, each block having on its inner surface a dovetail that fits into grooves *c*. The individual blocks are slipped on the core and then fastened in place by wedges that are inserted in the dovetail grooves. The heads of the binding rivets on the blocks serve as spacers for preserving the ventilating ducts. Blocks *d* are so shaped that a slot for a field coil is found between two adjacent blocks on

a circumference. Each of the blocks *e* has a straight side and a slot side, and, in conjunction with blocks *f*, which have two straight sides, serve to fill up the space between the sides of the narrowest field coils and form the center of the pole piece. The field coils are laid on the inner core, and the slotted laminated blocks are built up around them. This rotor when completed has four field coils per pole.

The portions of the coils that project from the slots must be firmly supported. In this rotor, the ends of the two inner coils of a group rest on retaining rings *g*, and the ends of

Fig. 51

the two outer coils rest on retaining rings *h*. Bolts that project through the end rings pass on both sides of the retaining rings and clamp the coils firmly between plates *a*, Fig. 51, and the retaining rings. These bolts also serve as spacers between the end portions of the coils. Ventilating holes *b* are provided in the end rings and plates, so as to give good circulation of air through the coil ends.

The completed rotor shown in Fig. 51 is part of a four-pole, 8,000-kilowatt turbo-alternator, and has a rated speed of 750 revolutions per minute. In this rotor, there are five

field coils per pole, but the general construction is similar to that shown in Fig. 50.

52. In all these turbo-alternator fields, cast metal is not depended on to withstand the stresses, and forged steel or laminated parts are used throughout. The field coils and poles are weighed separately before being put in place, and all parts are made as symmetrical as possible.

53. Ventilation for Field and Armature.—Cores for turbo-alternator fields are much longer in proportion to their diameter than those for ordinary types of alternator, thus making it more difficult to ventilate them thoroughly.

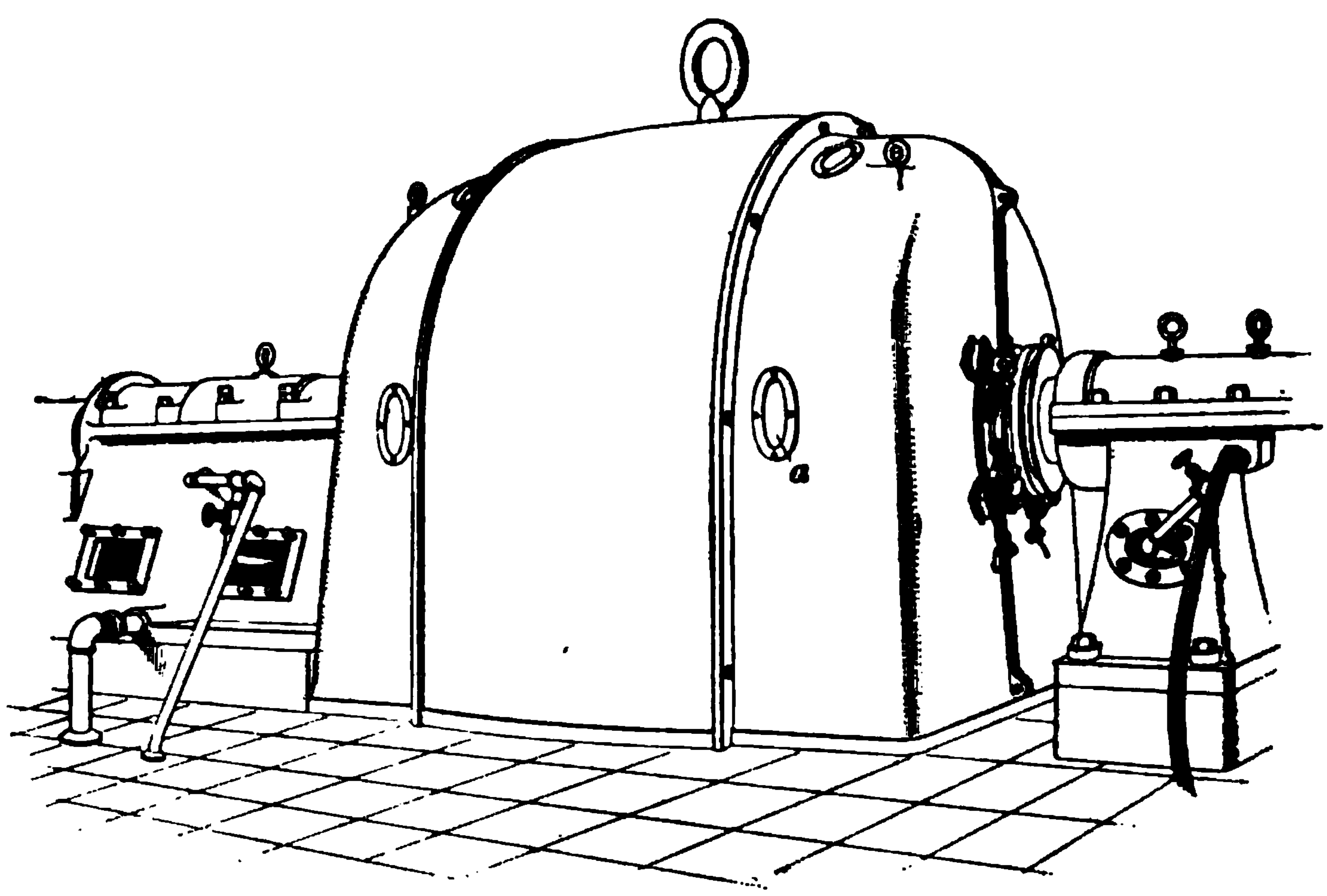


FIG. 52

The usual practice now is to make the whole frame enclosed and use forced air circulation through the generator, this circulation being set up either by fans mounted on the rotor or by an external blower. Besides the advantage of air circulation, the noise of the running machinery is very much reduced. In Fig. 52 is shown a Westinghouse enclosed turbo-alternator. The rotating parts, with the exception of the slip rings and the ends of the shaft, are enclosed by the alternator frame and end shields. The slip rings are on the end of the alternator, away from the steam turbine,

and are easily accessible. Handholes *a* are provided for inspecting the machine.

In Fig. 53, half of an end shield is removed in order to show the interior of the alternator. The air is taken in from

FIG. 53

large air ducts located just below the outer portion *a* of each end shield. A row of fan blades *b* is mounted on each end of the shaft, and the blades are so placed that air is forced into the space near the revolving field from both ends of

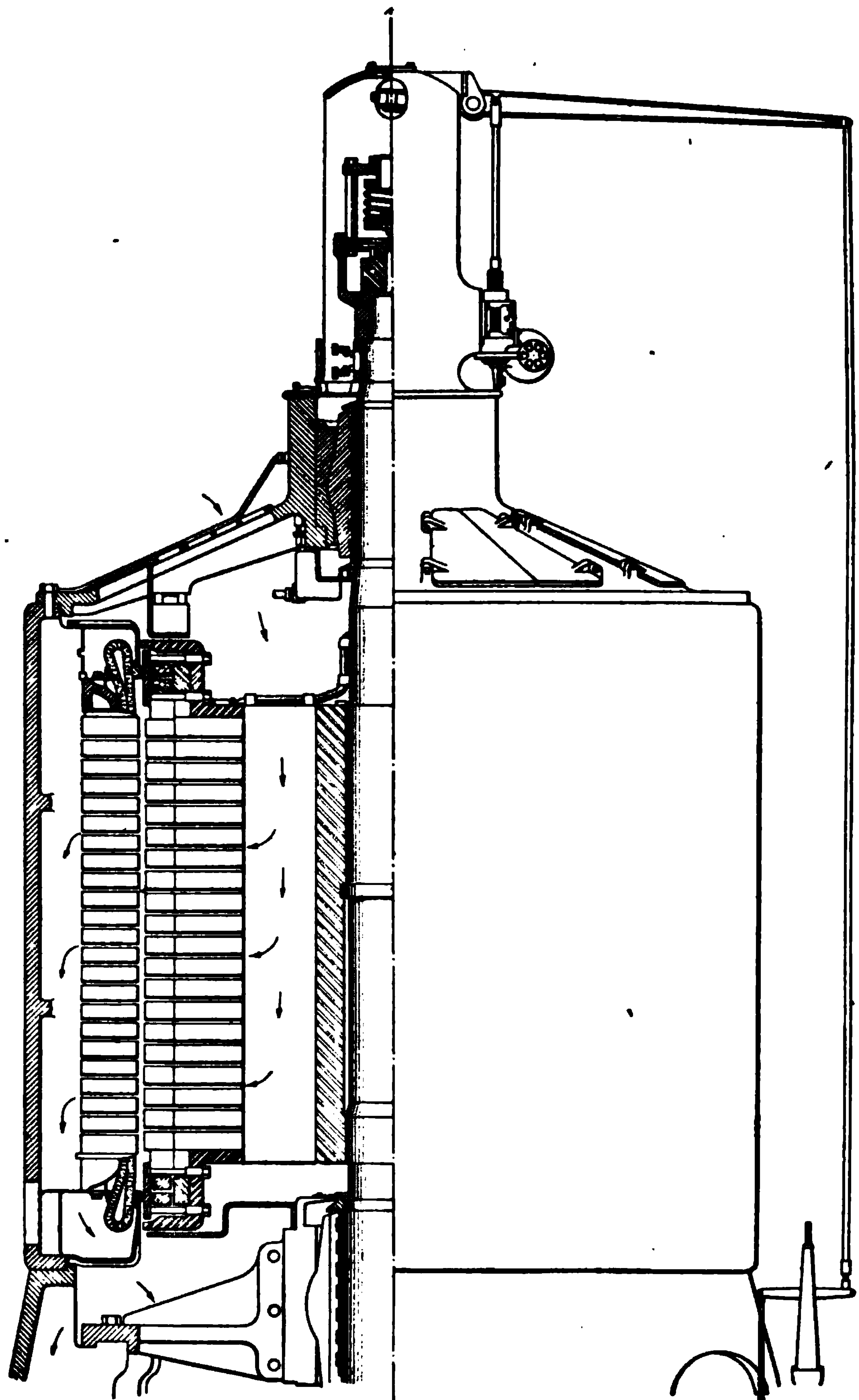


Fig. 54

the machine. The air is then caught up by the revolving field and forced through the ventilating ducts in the field and armature into the space between the armature core and the exterior frame. The air is then blown either down into the pit below the machine or out through holes near the top of the enclosing frame.

The projecting portions of the armature coils are held firmly in normal position by supports *c*. In other types of turbo-alternators, the armature-coil projections are held between an inner and an outer ring, the rings being mechanically connected together and to the machine frame.

54. In Fig. 54 is shown a turbo-alternator made by the General Electric Company and used for connection to a Curtis steam turbine. Air is admitted at the top of the alternator and passes into the space between the arms of the field spider. This air is then forced through the ventilating ducts in the field and armature, down between the armature core and exterior frame, and out of holes in the stool between the alternator and steam turbine.

COLLECTOR RINGS AND BRUSHES

55. With alternators having revolving armatures, **collector rings** are necessary to connect the armature winding with the external circuit, and the rings must be insulated to stand the full pressure generated in the armature. This was one of the objections to revolving-armature machines, since, with high potentials, it was not only difficult to insulate the rings and brushes, but there was considerable danger in working around them. With revolving-field generators, the rings need be insulated only for the pressure at which exciting current is supplied. It is desirable to wind the fields for excitation at low voltage, thereby reducing the number of turns on the field coils. If a high-voltage field winding with a large number of turns is used, very high electromotive forces will be induced in the coils in case the field circuit is suddenly broken, thus endangering the insulation. The general practice is to design the field windings for a maximum

electromotive force of 120 volts, except, perhaps, for some very large machines, where it may be desirable to wind for 250 volts. By winding for 120 volts, the fields can be excited from standard, 120-volt, direct-current generators or from an existing lighting circuit.

56. Brushes.—Carbon brushes are almost universally used on ordinary alternators for carrying the exciting current to the rings. The brushes are held in holders similar in construction to those previously described for direct-current machines, and in most cases the brushes are of the radial type. On the collector rings of rotary converters and on some turbo-alternators, copper brushes are frequently used. In every case, at least two brushes should be provided for each ring, even if one is sufficient to carry the current, for it may be necessary to examine or adjust a brush while the machine is running, and if at least two brushes per ring are used, this can be done without interrupting the exciting current. When a generator requires a large exciting current, several brushes are arranged around each ring so that there will be ample contact surface.

The current density at the contact surface between carbon brushes and cast-copper rings should not exceed 30 amperes per square inch. If cast-iron rings are used with carbon brushes, the density should not exceed 20 to 25 amperes per square inch. With copper brushes on copper rings, a density of 100 amperes per square inch of contact surface can be safely used.

The collector rings and brushes on a revolving-field alternator are a comparatively small part of the machine as regards cost, but if not properly designed and constructed, they may give considerable trouble. It is best, therefore, to be liberal in their design.

57. Examples of Collector-Ring Construction. There are various ways for mounting collector rings, some of which are especially suited to split rings, others to solid, and still others to cases where high insulation is essential. For large alternators, particularly those directly connected

to steam engines, the rings, together with the hub on which they are carried, should be split, so that they can be removed or mounted without disturbing the shaft or bearings. It is advisable to make the rings of open construction, so that air can circulate freely around them and promote the rapid radiation of heat.

Fig. 55 shows a construction used where high insulation is required, as, for example, on revolving-armature machines. The cast-copper rings *a* are carried on a cast-iron sleeve, or hub, *b*, and insulated therefrom by mica *c*. The rings are held in place by a collar *g* threaded on the sleeve *b*, and are separated from each other and from the end flange and collar by heavy insulating washers *d*, *d* made of seasoned veneer or vulcanite. The leads from the field winding are connected to the rings by means of two brass studs, one of which is shown at *e*; these studs are insulated by a mica or a paper tube *f*.

FIG. 55

58. Fig. 56 shows a very simple construction suitable for rings of comparatively small diameter. The sleeve is tapered and the rings, which are bored out to correspond with the taper of the sleeve, are forced directly on it. Connection is made to the field by studs screwed into the rings.

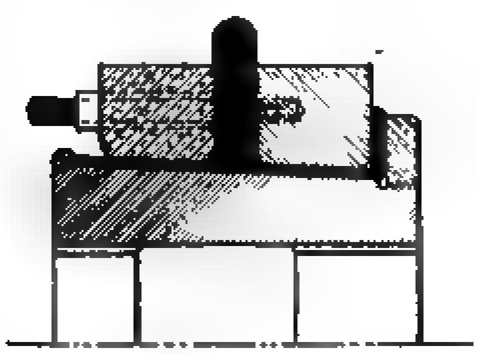


FIG. 56

Fig. 57 shows four methods of mounting the rings, (*a*) and (*b*) being particularly adapted to rings of rather small diameter. The mounting (*a*) is very simple, the rings being bored out on a taper and drawn together on a tapered seat by suitably insulated studs, which also serve to make the connection with the field leads. In (*b*) the rings are slipped over a hub.

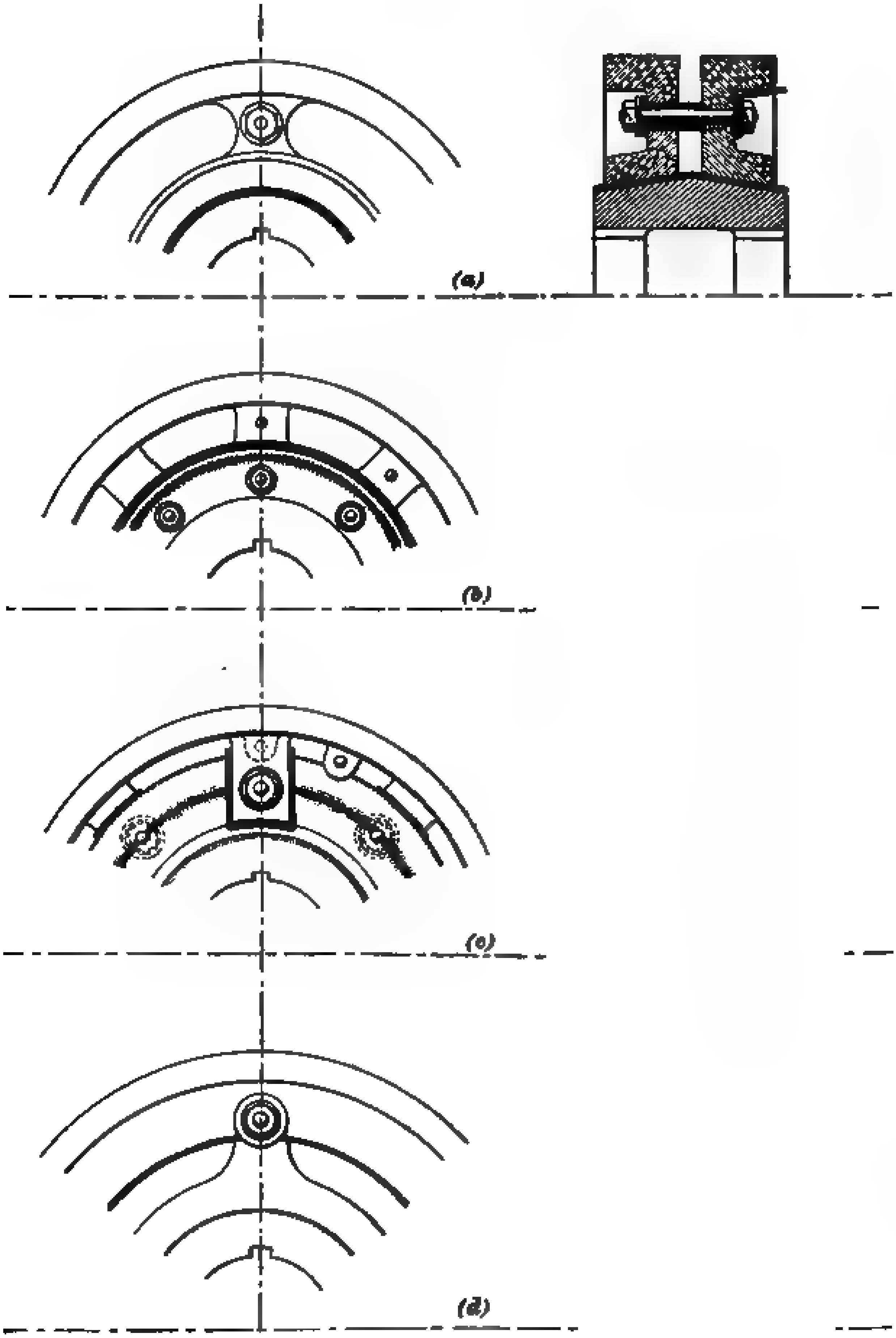


Fig. 57

The insulating collars that separate the rings from each other and from the clamping ring and hub are made cone-shaped, so that they cannot work out of place.

At (*c*) is shown a construction that has been used considerably with cast-iron rings, though it is equally suitable

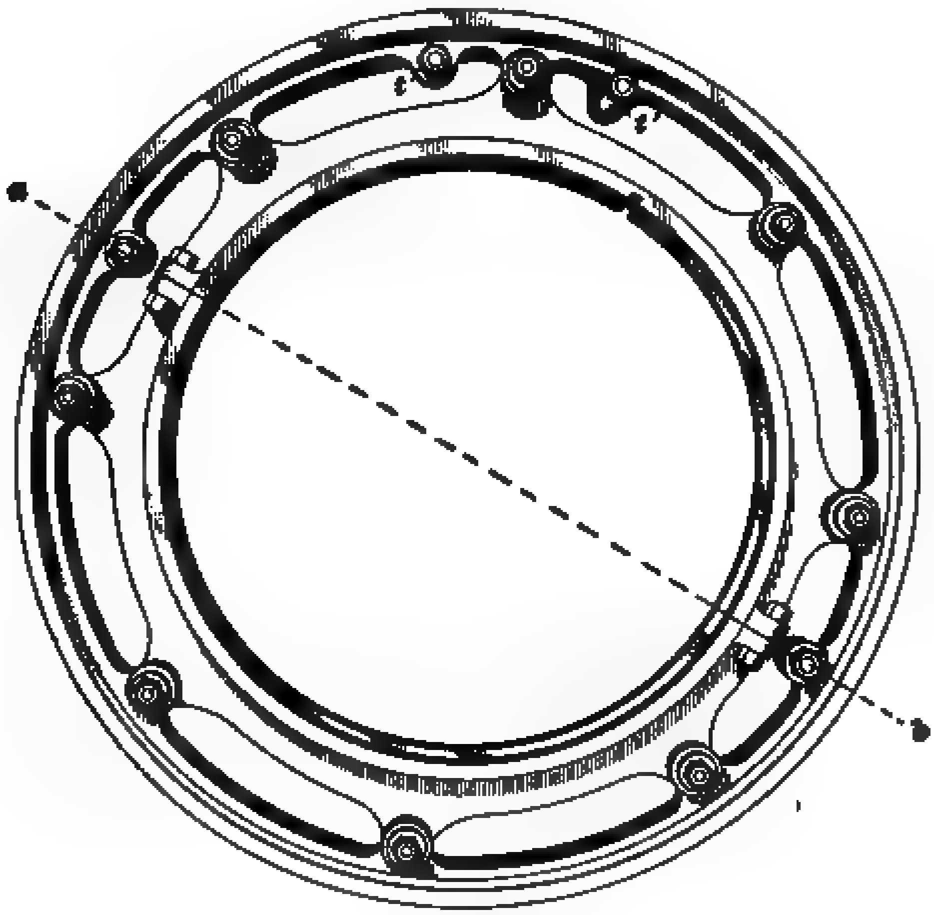


Fig. 58

for rings of copper. Each ring has a number of inwardly projecting lugs, which fit into V-shaped grooves on the hub, as shown, one ring being fastened to each side of the hub. The rings are insulated from the hub by cone-shaped mica washers, and when bolted tightly in place cannot shift or get out of true.

The mounting shown at (*d*) is much used for split rings of large diameter. The hub has a

Fig. 59

number of projecting arms, and insulated bolts both through the rings and the arms hold the rings in place. Fig. 58

shows a complete ring constructed in this manner. The hub and the rings are split along the line *a b*, and *t*, *t'* are the studs to which the field leads are attached.

Fig. 59 shows a construction very similar to Fig. 57 (*c*),

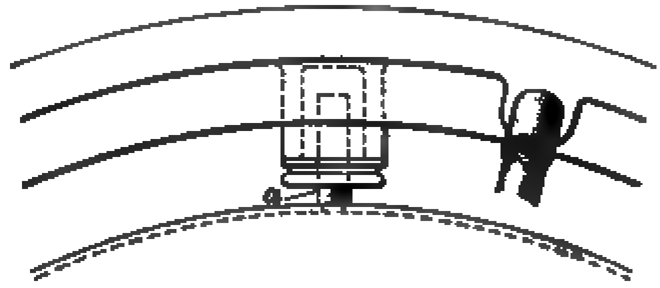


Fig. 60

except that both rings are attached to the same face of the hub—one by long arms, so that it overhangs the shaft. This method of mounting is sometimes convenient in special cases where space is limited or where it is desired to make the rings clear some other part of the machine.

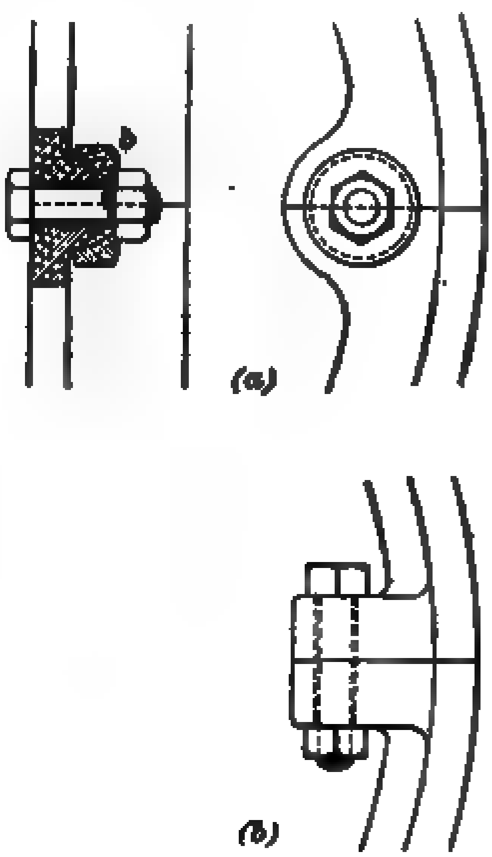


Fig. 61

59. Fig. 60 shows an interesting method of mounting in which no hub is provided. The rings are supported on pins *a*, which are thoroughly insulated by molded material *b*. The pins fit into shallow grooves *c*, *c* in the shaft, and one pin of each ring fits into a hole and thus prevents the rings from turning. When the halves of the ring are bolted together, the pins are clamped tightly against the shaft. This construction is simple, but it is hardly as substantial as the mounting on a hub; also, the rings are more liable to run out of true.

Fig. 61 shows two methods of making joints for split rings. In (*a*), a conical washer *b* is forced against a conical seat, thus drawing the halves of the ring together.

In (*b*), the halves are drawn up by a bolt passing through two lugs.

60. Brush-Holder Supports.—Brush holders are generally supported on studs, which allow adjustment so that the brush can be centered on the rings. Fig. 62 shows the most common method of mounting and insulating these studs. The stud *a* is supported by a casting *f*, from which it is insulated by an ebonite or molded insulation sleeve *l* and washers *b*, *b*. Shoulder *c* is part of stud *a*. The terminal wire is soldered into terminal *d*, and nut *e* clamps the stud in place. The hole in *f* is elongated, so that the studs can be

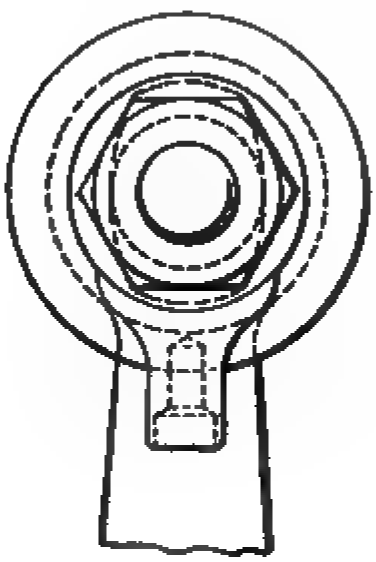


FIG. 62

shifted up or down slightly. In small alternators, the supporting casting *f* is usually attached to one of the bearing caps or pedestals.

Fig. 63 shows the general arrangement of collector rings and brushes on a small Bullock alternator. On the rings *a* rub carbon brushes *b*, which are pressed down by fingers *c* hinged to the brush-holder frame. The pressure on the brushes is maintained by springs *e*, the tension of which can be adjusted by placing their supporting casting *c'* in the different notches in the forks of the fingers. Woven-wire shunts, or pigtails, *d* connect the brush directly to the holder, so that current does not pass through the pressure arms or the springs. The brush studs *f* are supported by a casting *g*,

which has elongated holes in it so that the studs can be shifted up or down through a short distance, thus allowing the brushes to be adjusted with reference to the rings. The supporting casting is bolted to the bearing *h*. The connec-

Fig. 62

tions leading to the field winding are shown at *k*. These connections consist of two copper strips suitably insulated, tightly bound together with a cord covering, and fastened to the shaft by suitable brass cleats held in place by small cap-screws.

61. With very large alternators, it is not usually practicable to support the brush studs from the bearing, and it is therefore necessary to provide some form of stand that can be bolted to the bed of the machine or, in case the alternator is of the direct-connected engine type and has no base of its own, to a bridge attached to the sole plates. Fig. 64 shows a brush stand of this kind. The cables leading to the brush studs pass up through the hollow pedestal *a* and then are connected to the brush-holder studs on which are mounted brush holders *b*. The brush holders *b* are of the same general construction as those shown in Fig. 63, but are designed for brushes of greater carrying capacity in order to transmit the increased field current necessary for alternators of large output. In Fig. 64 the brushes have been removed.

FIG. 64

DESIGN OF ALTERNATING-CURRENT APPARATUS

(PART 3)

DESIGN OF A 250-KILOWATT ALTERNATOR

1. Specifications.—In order to illustrate the application of the foregoing principles, the design of a 250-kilowatt alternator of engine type, suitable for direct connection to a high-speed engine, will be worked out. In the calculations for dynamo or alternator design, the results are seldom carried beyond three significant figures, as the assumptions on which the calculations are based are no more accurate than this.

The alternator to be designed is of the revolving-field type, as follows:

Output	250 kilowatts
Speed	180 revolutions per minute
Frequency and phase	60 cycles, three phase
Volts	2,200

The maximum exciting voltage available is 125. The efficiency is to be not less than 93.5 per cent. at full load, 92.5 per cent. at three-quarters load, and 90 per cent. at half load. These efficiencies do not include windage or friction, as these are considered as part of the engine loss with direct-connected engine-type generators.

The regulation is not to exceed 8 per cent. when full-load current at power factor 1 is thrown off, nor 20 per cent. with full-load current at power factor .8. The alternator is to

carry full non-inductive load continuously, with a temperature rise not exceeding 40° C. above the surrounding air.

2. Preliminary Calculations.—The frequency $n = \frac{ps}{2}$, where the revolutions per second $s = \frac{\text{R. P. M.}}{60}$. Substituting in this formula the values assumed for the alternator to be designed and solving the equation, the *number of poles*

$$p = \frac{120 \times 60}{180} = 40$$

The output of an alternator, in watts, on power factor 1 is $\sqrt{3}\,E\,I$; hence, the *current per phase*

$$I = \frac{\text{watts}}{\sqrt{3}\,E} = \frac{250{,}000}{\sqrt{3} \times 2{,}200} = 65.6 \text{ amperes}$$

DESIGN OF ARMATURE

CORE DIMENSIONS

3. The approximate dimensions—length and diameter—of the armature core is found by means of the output formula

$$W = \frac{k_w d^2 l \,\%\, \mathbf{B}_g K S}{5.48 \times 10^8}$$

or,

$$d^2 l = \frac{5.48 \times 10^8\, W}{k_w \,\%\, \mathbf{B}_g K S}$$

Since this is to be a three-phase machine for 2,200 volts—a comparatively low pressure—there should be no difficulty in using a two-layer winding with two slots per pole per phase. The value of k_w will therefore be .965. For a machine of this size, speed, and voltage, it is safe to assume that the poles will cover 62.5 per cent. of the armature surface; that is, $\% = .625$. As this is a 60-cycle machine, the average air-gap density $\mathbf{B}_g$ will be taken at 45,000 lines per square inch. K, the ampere-conductors per inch of periphery, will be taken at a conservative value of 450. $W = 250{,}000$, since the output is 250 kilowatts, and $S = 180$. Then, the *cylindrical inches*

$$d^2 l = \frac{5.48 \times 10^8 \times 250{,}000}{.965 \times .625 \times 45{,}000 \times 450 \times 180} = 62{,}300, \text{ approximately}$$

As the diameter of the armature is not specified or limited in any way by the use of existing punchings, it will be made such as to give a length of core, not including air ducts, about equal to the pole pitch. This will make the pole of an economical shape.

$$\text{Pole pitch} = \frac{\pi d}{p},$$

where d is the diameter of the armature. If l is the spread of the iron laminations, then, according to the assumption just made,

$$\frac{\pi d}{p} = l$$

$$d^2 l = d^2 \frac{\pi d}{p} = \frac{\pi d^3}{p}$$

But, $$d^2 l = 62{,}300$$

Hence, $$\frac{\pi d^3}{p} = 62{,}300$$

and

$$d = \sqrt[3]{\frac{62{,}300 p}{\pi}} = \sqrt[3]{\frac{62{,}300 \times 40}{3.1416}} = 92.6 \text{ in., approximately}$$

It will be better to make the diameter an even 90 inches and lengthen the core a little to make up for the smaller diameter. Then, $d^2 l = 62{,}300$, $d = 90$ inches, and

$$l = \frac{62{,}300}{90^2} = 7.7 \text{ inches}$$

The spread of the iron laminations will be taken as 7¾ inches. Two ½-inch air ducts will be placed in the core and two more between the core and the end plates, the laminations being divided into three sections. One section will be 2¾ inches wide, and each of the others 2½ inches, as shown in Fig. 1, thus making the required 7¾ inches of laminations. The pole has no ducts, and its total length will be 7¾ inches, made up of 7 inches of laminations and two malleable-iron end heads each ⅜ inch thick.

4. Number of Slots.—As this machine is to be three-phase, the **number of slots** must be divisible by 3. Two slots per pole per phase was assumed in deciding the core dimensions; hence, there will be six slots per pole. This

number also has the advantage that it is suitable for a two-phase machine. There are forty poles; hence, the total number of slots is 240.

FIG. 1

5. Flux per Pole.—In order to calculate the **flux per pole**, it is first necessary to calculate the pole area. For preliminary calculations, it is sufficiently accurate to assume that the diameter of the rotating field is the same as that of the armature, that is, to make no allowance for the air gap. If the air gap determined is so long as to make any great change in the calculations, corrections may be necessary.

$$\text{Pole pitch} = \frac{\pi d}{p} = \frac{3.1416 \times 90}{40} = 7.07 \text{ inches}$$

Pole arc = pole pitch × % = 7.07 × .625 = 4.42 inches

The length of the pole face is $7\frac{3}{4}$ inches; hence,

$$\begin{aligned}\text{area of pole face} &= 4.42 \times 7.75 \\ &= 34.2 \text{ square inches, approximately}\end{aligned}$$

The average air-gap density has been taken at 45,000 lines per square inch; hence,

$$\begin{aligned}\Phi &= \text{pole area} \times \text{average density} = 34.2 \times 45{,}000 \\ &= 1{,}540{,}000 \text{ lines, nearly}\end{aligned}$$

6. Turns per Phase.—Since the flux per pole is now known, the number of **turns per phase** can be calculated from the formula

$$E_p = \frac{4.44\, \Phi\, T_p\, n}{10^8} k_w$$

k_w, for a three-phase winding with two slots per pole per phase = .965; n = 60; Φ = 1,540,000. The winding will be Y-connected; hence, the volts per phase E_p will be equal to the volts between lines divided by $\sqrt{3}$.

$$E_p = \frac{2,200}{\sqrt{3}} = 1,270$$

and $$1,270 = \frac{4.44 \times 1,540,000 \times T_p \times 60 \times .965}{10^8}$$

or, $$T_p = \frac{1,270 \times 10^8}{4.44 \times 1,540,000 \times 60 \times .965} = 321, \text{ nearly}$$

The total number of conductors per phase is 2 T_p, or 642. There are 240 slots total, or 80 slots per phase, hence, 8 conductors per slot will give 640 conductors per phase, which is within 2 of the required number. By strengthening the field slightly, 640 conductors per phase can be made to generate the required voltage. In this case, the number selected comes out so nearly the same as the calculated number that it will not be necessary to make any change in the length of the core. If there were a very large discrepancy, it would be necessary to lengthen or shorten the core enough to make the flux such that the number of conductors would suit the number of slots.

7. Dimensions of Slot and Insulation.—For 2,200 volts, a satisfactory slot insulation can be made of one layer of .012-inch leatheroid, one layer of .02-inch mica, and three layers of .015-inch varnished cloth, half-lapped, the total thickness of cloth being .045 inch.

For the conductor, an allowance of 750 circular mils per ampere is sufficient. Since the armature is Y-connected, the full-load current per line is the same as the current per phase, that is, 65.6 amperes.

$$\text{Circular mils} = 750 \times 65.6 = 49,200$$

No. 4 B. & S. round wire has 41,700 circular mils, while No. 3 has 52,600. No. 4 square wire has 41,700 ÷ .7854 = 53,000 circular mils, approximately. However, an allowance of at least 7 or 10 per cent. must be deducted for rounded corners; hence, No. 4 square wire with rounded corners has

a cross-sectional area of 49,000 circular mils, approximately, and this size can be used.

The slot pitch, or distance between slot centers, is $\frac{90 \times \pi}{240} = 1.18$ inches. The width of the slot opening should not be much in excess of .6 of the slot pitch, otherwise the density in the teeth will be too high.

8. Fig. 2 shows the slot with its eight conductors *f*, *f* of No. 4 square wire. The winding is of the two-layer type; hence, each coil has four turns. The eight conductors in a slot are in two groups of four conductors each. The square conductor has well-rounded corners and is double cotton-covered. An allowance of 8 mils (.008 inch) is made for the thickness of this covering; that is, the over-all dimensions of the conductor will be increased 16 mils, due to the cotton insulation. The layer of leatheroid is shown at *a*; it is lapped over on top of the coil (the side nearest the slot opening) as is also the layer of mica *b*. The three layers of half-lapped linen tape are shown at *c*, and *d* is the cotton wrapping around the wire. A 12-mil layer of leatheroid *e* is placed vertically in the coil to separate the layers. The bare No. 4 wire is .204 inch square, and .204 + .016 = .22 inch over the double-cotton insulation.

Fig. 2

The slot, then, must be wide enough to contain the following:

	Inch
Three layers of .012-inch leatheroid (*a*)	.036
Two layers of .02-inch mica (*b*)	.040
Six layers of .015-inch varnished cloth (*c*)	.090
Two insulated conductors	.440
Total width of slot required	.606

The slot should be made $\frac{5}{8}$ inch wide, allowing $.625 - .606 = .019$ inch for clearance.

The slots must be deep enough to contain two sides of coils and a wooden retaining strip. With the exception of the overlapping layer of .02-inch mica on top of the coil, the space occupied by a side of a coil is the same in depth as in width. The absence of layer *e* neutralizes the lap of the outer leatheroid cover in the calculation for the depth of the coil. This makes the depth of a coil $.606 + .02 = .626$ inch. Allowing $\frac{5}{32}$ ($= .156$) inch for the thickness of the retaining strip, makes the total depth required $2 \times .626 + .156 = 1.408$ inches. The slot should be made $1\frac{7}{16}$ ($= 1.4375$) inches deep, thus allowing $1.4375 - 1.408 = .0295$ inch for clearance.

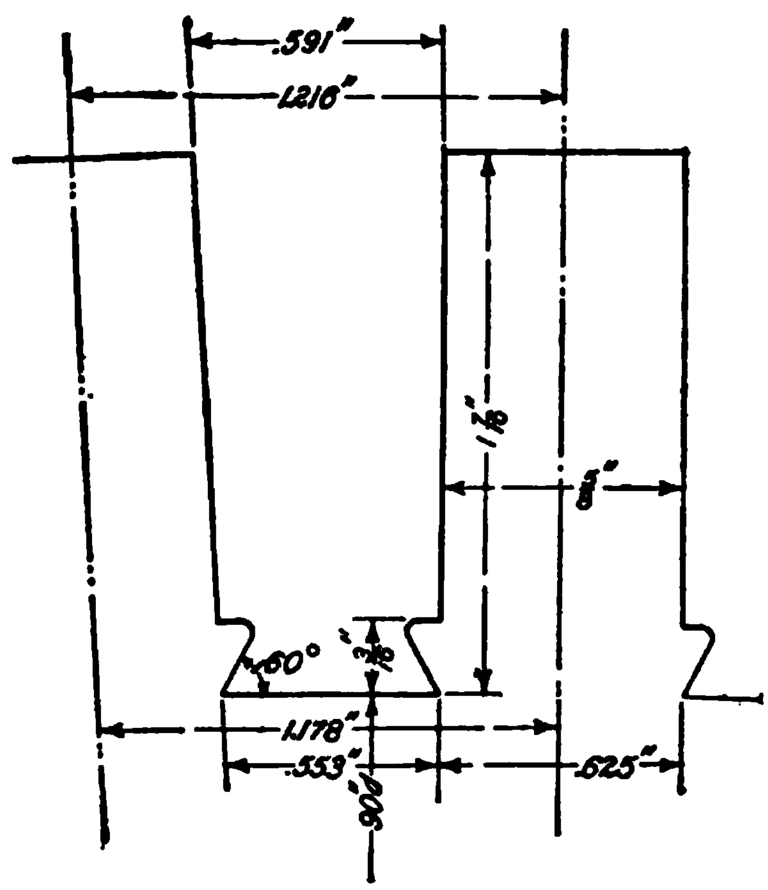


Fig. 3

The nicks in the teeth, provided for the holding stick, will be as shown in Fig. 2. Fig. 3 shows a slot and tooth. The tooth width at the circumference is .553 inch and at the bottom, or root, .591 inch. The tooth pitch at the roots is 1.216 inches, and at the circumference $.553 + .625 = 1.178$, or 1.18, inches, approximately.

9. Depth of Iron Under Slots.—After passing through the teeth, the flux from each pole divides, one-half passing each way through the armature core to the next adjacent pole. The depth of iron d_c, Fig. 1, must therefore be sufficient to carry half the total armature flux without making the density too high.

The flux passing through the core under the teeth is $1{,}540{,}000 \div 2 = 770{,}000$, and as the core should be worked at a density of about 35,000 lines per square inch, the

cross-section of iron under slots is 770,000 ÷ 35,000 = 22 square inches.

The spread of the iron laminations is 7¾ inches; assuming that 90 per cent. of this is iron and 10 per cent. insulating varnish or japan, the net iron is 7.75 × .9 = 6.975 inches.

The depth of iron under slots is

$$\frac{\text{area}}{\text{net length}} = \frac{22}{6.975} = 3.15 \text{ inches}$$

The depth will therefore be made 3¼ inches, thus giving a net cross-section of iron of 3.25 × 7.75 × .9 = 22.7 square inches, and an actual density of 770,000 ÷ 22.7 = 34,000 lines per square inch, approximately.

The armature punchings will be in segments having twelve slots per segment; and twenty segments will be required for one complete round of the armature lamination. The laminations will be .014 inch thick.

AIR GAP

10. The **air gap** must be chosen with reference to the magnetizing power of the armature, and will be made of such length that the ampere-turns on the field required to set up a density of 45,000 lines per square inch in the air gap will be approximately 2.5 times the ampere-turns per pole on the armature. The armature ampere-turns per pole can be obtained approximately from the formula

$$\text{armature ampere-turns per pole} = .707\, m\, T_{pp}\, I_p$$

There are sixteen conductors, or eight turns per pole per phase; hence, $T_{pp} = 8$; $m = 3$; $I_p = 65.6$. Thus, the armature ampere-turns per pole = .707 × 3 × 8 × 65.6 = 1,110, approximately, making the field ampere-turns per pole for the air gap 1,110 × 2.5 = 2,775. The length of the air gap must be

$$l_g = \frac{I T_g}{.313\, \mathbf{B}_g} = \frac{2{,}775}{.313 \times 45{,}000} = .197 \text{ inch, approximately}$$

Therefore, the air gap will be made .2 inch.

PROPORTIONS OF MAGNETIC CIRCUIT

11. Dimensions of the Pole.—The pole pitch (7.07 inches) and the pole arc (4.42 inches) have already been determined. The chord of the pole arc is practically the same as the arc itself, and in practice both would be taken as $4\frac{7}{16}$ inches. The value of % would then be $4.4375 \div 7.07 = .628$.

In order to calculate the cross-section of the pole cores, it is necessary to know the magnetic flux through a pole. This is greater than the flux entering the armature because of the field leakage. To calculate the flux through a pole, the leakage coefficient must be known, but this coefficient cannot be estimated until the dimensions of the poles have been fixed. However, for the present purpose, it is accurate enough to assume an approximate value of the leakage coefficient, while the more exact value can be calculated later. For an alternator of this type, the leakage coefficient will be in the neighborhood of 1.2. The useful flux per pole is 1,540,000 lines; hence, taking 1.2 for the leakage coefficient,

$$\text{flux in pole} = 1{,}540{,}000 \times 1.2 = 1{,}848{,}000 \text{ lines}$$

Since the poles will be built up of steel stampings, a fair value for the density in the pole cores is 90,000 lines per square inch.

$$\text{Area of pole section} = \frac{1{,}848{,}000}{90{,}000} = 20.53 \text{ square inches}$$

The length of a pole core measured parallel with the shaft is $7\frac{3}{4}$ inches, and the laminations will be at least .025 inch (25 mils) thick. The net length of iron in a core may be taken as 95 per cent. of the gross core length, because the pole laminations are comparatively thick and the percentage of space not occupied by iron is smaller than in the armature. Hence, the net length of iron in a pole is $7.75 \times .95 = 7.36$ inches, approximately, and the width of each pole core is $20.53 \div 7.36 = 2.79$ inches.

Each pole core will therefore be made $2\frac{7}{8}$ inches wide. The length of the pole measured radially remains to be fixed, but this cannot be decided definitely until after the

field winding has been calculated. For this type of machine, the pole cores are usually from 2 to $2\frac{1}{2}$ times as long, radially, as they are broad, and for purposes of further calculation the length will be taken as $2 \times 2\frac{7}{8} = 5\frac{3}{4}$ inches. This dimension can easily be corrected later in case it is found that the pole is a little too long or too short.

12. Spider Rim.—The field spider will be made of cast steel and the poles will be bolted on. The steel in the

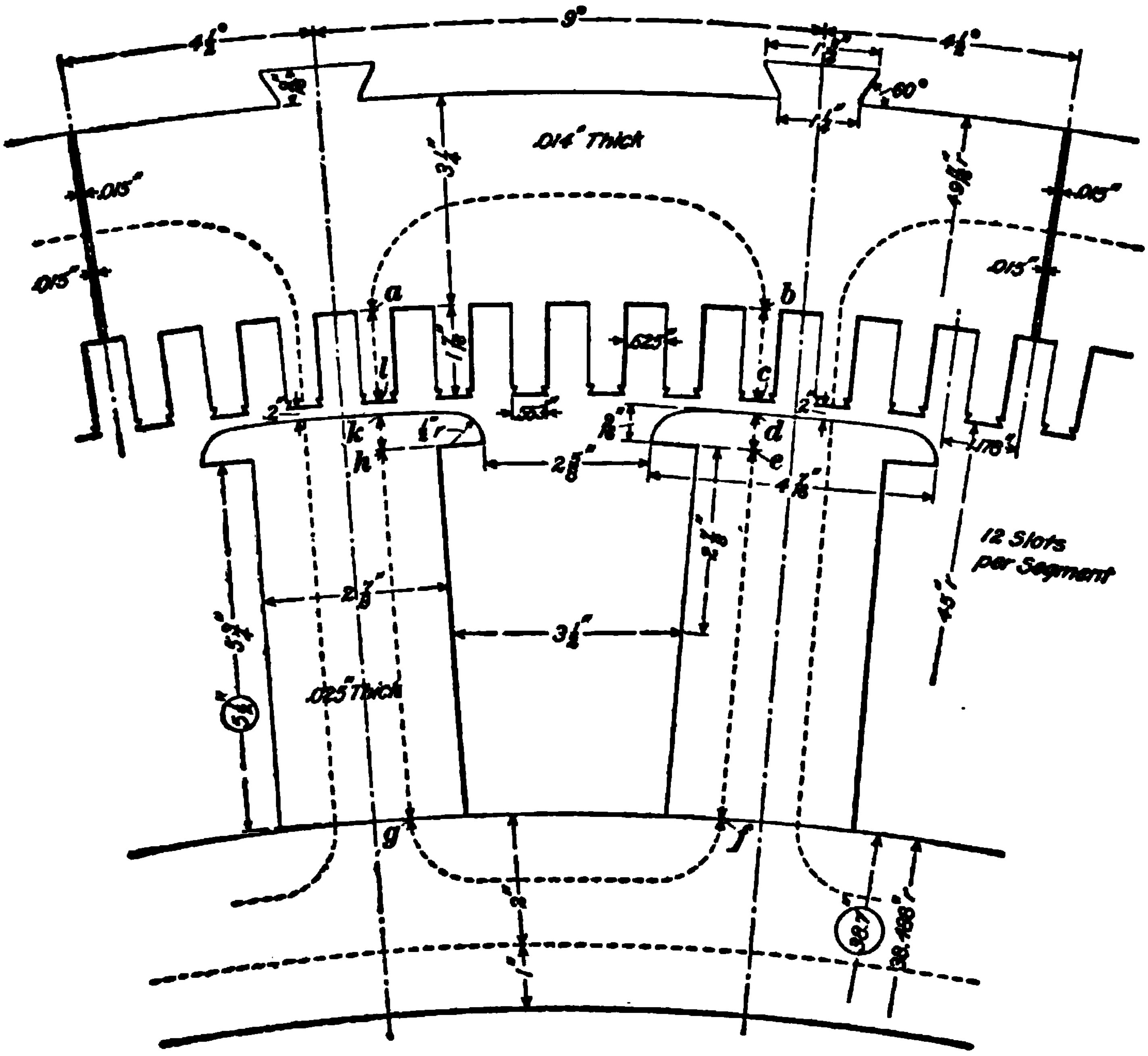


FIG. 4

spider could be worked up to a density of 60,000 or 70,000 lines per square inch, but this would make a rim that would be very light and not strong enough mechanically. The poles are $7\frac{3}{4}$ inches long, measured parallel with the shaft, and in order to allow for a projection at each end for the coils to rest on, a preliminary width of $9\frac{1}{2}$ inches for the rim will be taken. The rim will be 2 inches thick, with a flange on

each side to add stiffness and to improve the appearance. The cross-section of the rim may therefore be taken as 20 square inches, approximately. The flux in the rim is 1,848,000 ÷ 2 = 924,000 lines, thus making the density 924,000 ÷ 20 = 46,200 lines per square inch.

All preliminary dimensions of the field and armature punchings and the field spider have now been obtained, and the complete magnetic circuit is as shown in Fig. 4.

13. Leakage Flux.—The **leakage flux** and **leakage coefficient** can now be calculated approximately, since the pole dimensions are known. Any slight change that may be required later in the radial length of the pole core will not affect the leakage appreciably. The formula for the leakage flux, as given in *Design of Alternating-Current Apparatus*, Part 1, is

$$\Phi_l = 3.19\,X\left[\left(\frac{4\,h'}{a'} + \frac{2\,h}{a}\right)L + 3.2\,h\,k + 6.42\,h'\,k'\right]$$

The dimensions of the teeth and slots, as shown in Fig. 4, are $h' = \frac{9}{16}$, or .563, inch; $a' = 2\frac{5}{8}$, or 2.625, inches; $h = 5.75$ inches; $a = 3.5$ inches; $w = 2\frac{7}{8}$, or 2.875, inches; and $w' = 4\frac{7}{16}$, or 4.4375, inches.

The length L of the pole parallel with the shaft is 7.75 inches. The values of k and k' may be obtained from the curves in *Design of Alternating-Current Apparatus*, Part 1.

$$\frac{w}{a} = \frac{2.875}{3.5} = .82\text{, approximately, and } k = .365$$

$$\frac{w'}{a'} = \frac{4.4375}{2.625} = 1.69\text{, nearly, and } k' = .562$$

$$\Phi_l = 3.19\,X\left[\left(\frac{4 \times .563}{2.625} + \frac{2 \times 5.75}{3.5}\right)7.75 + 3.2 \times 5.75 \times .365 + 6.42 \times .563 \times .562\right] = 130.4\,X\text{, nearly}$$

From this result, the leakage flux may be calculated when the ampere-turns per pole X required to set up the useful flux through the air gap are known.

ESTIMATION OF FIELD AMPERE-TURNS

14. Effective Air Gap.—Before the ampere-turns for the air gap can be closely estimated, the active length and area of the gap must be calculated as explained in *Design of Alternating-Current Apparatus*, Part 1. The actual air gap l_g is .2 inch; the width of slot opening s, .625 inch; and the width of tooth t, .553 inch. On account of the bunching of the lines at the tooth tops, the effective air gap used in the calculations must be greater than the actual air gap. The effective air gap is determined by the formula

$$l'_g = \left\{ \frac{1 + \frac{s}{t}}{1 + k' \frac{s}{t}} \right\} l_g$$

The coefficient k' depends on the ratio $\frac{s}{l_g} = \frac{.625}{.2} = 3.125$, and from the curve previously given the corresponding value of k' is found to be .62. Substituting the values in the formula, the effective air gap

$$l'_g = \left(\frac{1 + \frac{.625}{.553}}{1 + .62 \frac{.625}{.553}} \right) \times .2 = 1.25 \times .2 = .25 \text{ inch}$$

15. Effective Polar Arc.—On account of the fringing of the lines of force at the pole corners,

effective polar arc = actual arc + $k\,l_g$

The value of k depends on the ratio

$$\frac{\text{pole pitch} - \text{pole arc}}{l_g} = \frac{7.07 - 4.4375}{.2} = 13.16$$

The corresponding value of k from the curve previously given is 2.8, and

effective arc = $4.4375 + 2.8 \times .2 = 4.998$, say 5, inches

There will be some fringing at the ends of the pole face, and to allow for this it will be close enough to add the depth of the air gap, .2 inch, to the pole face; that is, take the effective pole length as $7.75 + .2 = 7.95$ inches.

16. Effective Air-Gap Density.—The **effective density** in the air gap is found by dividing the flux per pole by the effective pole-face area. The flux per pole in the air gap is 1,540,000 when the machine is delivering normal voltage. The effective pole area is $7.95 \times 5 = 39.75$ square inches; hence,

$$\text{effective air-gap density} = \frac{1{,}540{,}000}{39.75}$$
$$= 38{,}800 \text{ lines per square inch}$$

With no allowance for fringing, the density was 45,000 lines per square inch.

$$\text{Ampere-turns per pole for air gap} = .313 \times 38{,}800 \times .25$$
$$= 3{,}036$$

Although the pole fringing reduces the effective density, the effect of this correction is more than offset by the increase in the effective gap length. For example, with an air-gap density of 45,000 and an effective gap of .2 inch (the same as the actual gap), the ampere-turns per pole for the air gap would be $.313 \times 45{,}000 \times .2 = 2{,}817$.

17. Leakage Coefficient.—With 3,036 ampere-turns per pole for the air gap, the leakage flux will be

$$\Phi_l = 130.4 \times 3{,}036 = 396{,}000 \text{ lines}$$

$$\begin{aligned} \text{Leakage flux} &= 396{,}000 \\ \text{Useful flux} &= \underline{1{,}540{,}000} \\ \text{Total flux} &= 1{,}936{,}000 \end{aligned}$$

$$\text{Leakage coefficient} = \frac{1{,}936{,}000}{1{,}540{,}000} = 1.26, \text{ nearly}$$

This coefficient is but little greater than the original assumed value of 1.2.

18. Density in Pole Core, Shoe, and the Spider Rim.—The flux through the whole length of the pole core may be taken as 1,936,000. This is not quite true, however, as, owing to the leakage decreasing from the pole face down to the spider rim, the flux in the core is greater near the spider than it is near the pole face; nevertheless, it is on the safe side to consider the flux the same all through the pole core, and it is not worth while to make any correction for the variation.

The breadth of the pole core is 2.875 inches and the net length of iron 7.36 inches; hence,

$$\text{pole-core density} = \frac{1{,}936{,}000}{2.875 \times 7.36} = 91{,}500 \text{ lines per square inch, nearly}$$

The flux in the pole shoe may be taken the same as in the air gap, as most of the leakage takes place from the field cores; hence,

$$\text{pole-shoe density} = \frac{1{,}540{,}000}{4.4375 \times 7.36} = 47{,}200 \text{ lines per square inch, nearly}$$

Taking the cross-sectional area of the spider rim as 20 square inches, then,

$$\text{density in spider rim} = \frac{\frac{1}{2} \times 1{,}936{,}000}{20} = 48{,}400 \text{ lines per square inch}$$

19. Density in Armature Teeth and Core.—There is a total of 240 teeth in the armature, or 6 per pole. Since the pole covers .625 of the pole pitch, there are $.628 \times 6 = 3.77$ teeth opposite each pole. The total area of the ends of the teeth opposite a pole is $3.77 \times .553 \times 7.75 \times .9 = 14.5$ square inches, approximately. The average tooth cross-section is slightly greater than this, but it will be on the safe side to consider 14.5 as the tooth section for carrying the flux.

$$\text{Density in teeth} = \frac{1{,}540{,}000}{14.5} = 106{,}000 \text{ lines per square inch}$$

The armature core was first calculated of such depth as to give a density of 34,000 lines per square inch, and no change has been made in its cross-section.

20. Length of Magnetic Circuit.—In estimating the ampere-turns per pole, a complete magnetic circuit, as shown by the dotted line *a–b–c–d–e–f–g–h–k–l–a*, Fig. 4, must be considered. This will give the ampere-turns for a pair of poles, and the result divided by 2 will be the ampere-turns per pole. The lengths of the paths through the various parts, as scaled off the drawing, are as follows:

	INCHES
Armature core $a\ b$	8.75
Teeth $= 2 \times bc = 2 \times 1\frac{7}{16}$	2.875
Pole shoes $= 2 \times de = 2 \times \frac{9}{16}$	1.125
Pole cores $= 2 \times ef = 2 \times 5\frac{3}{4}$	11.5
Spider rim $= fg$	6.
Air gap (effective) $= 2 \times .25$	.5

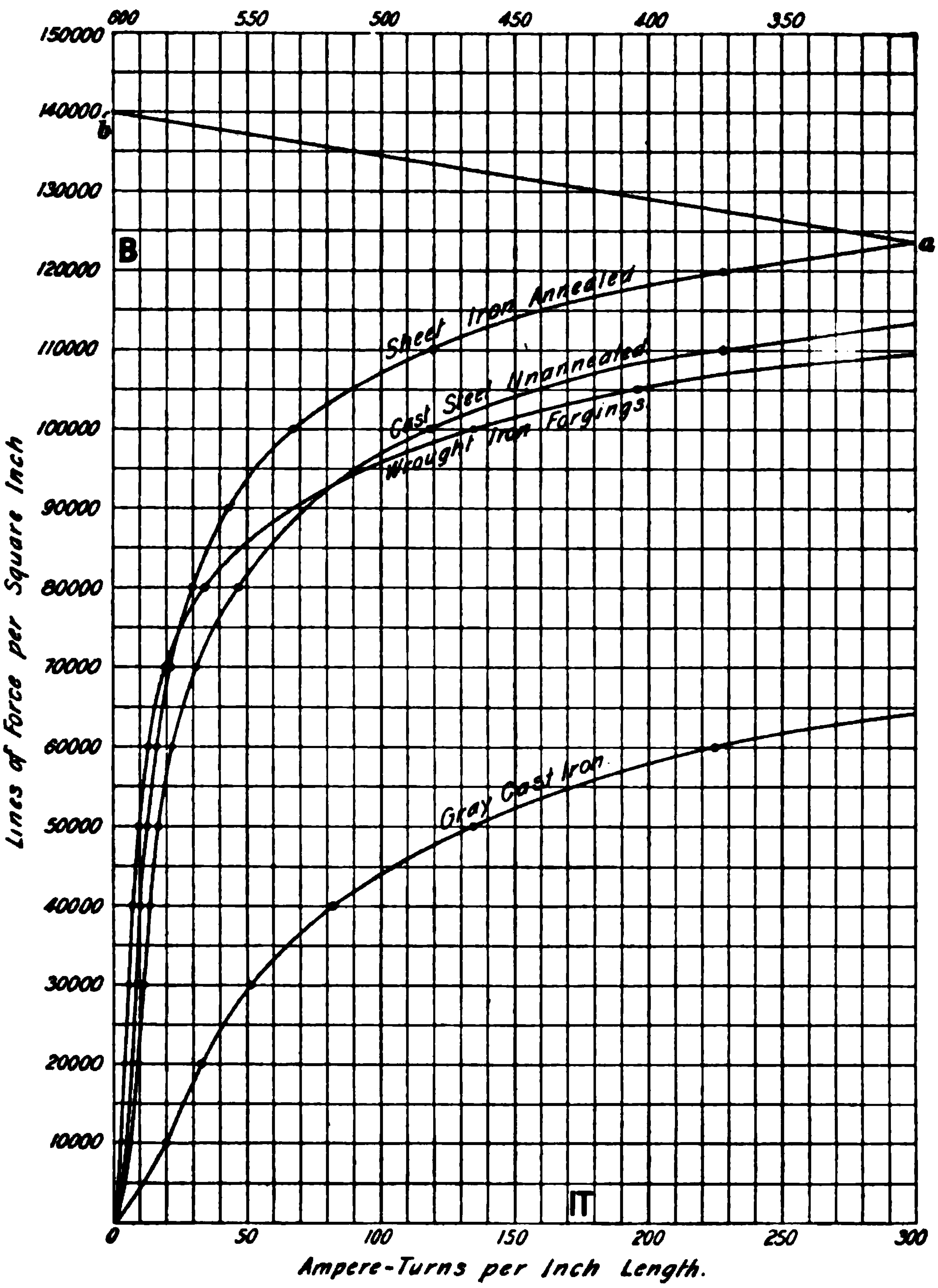


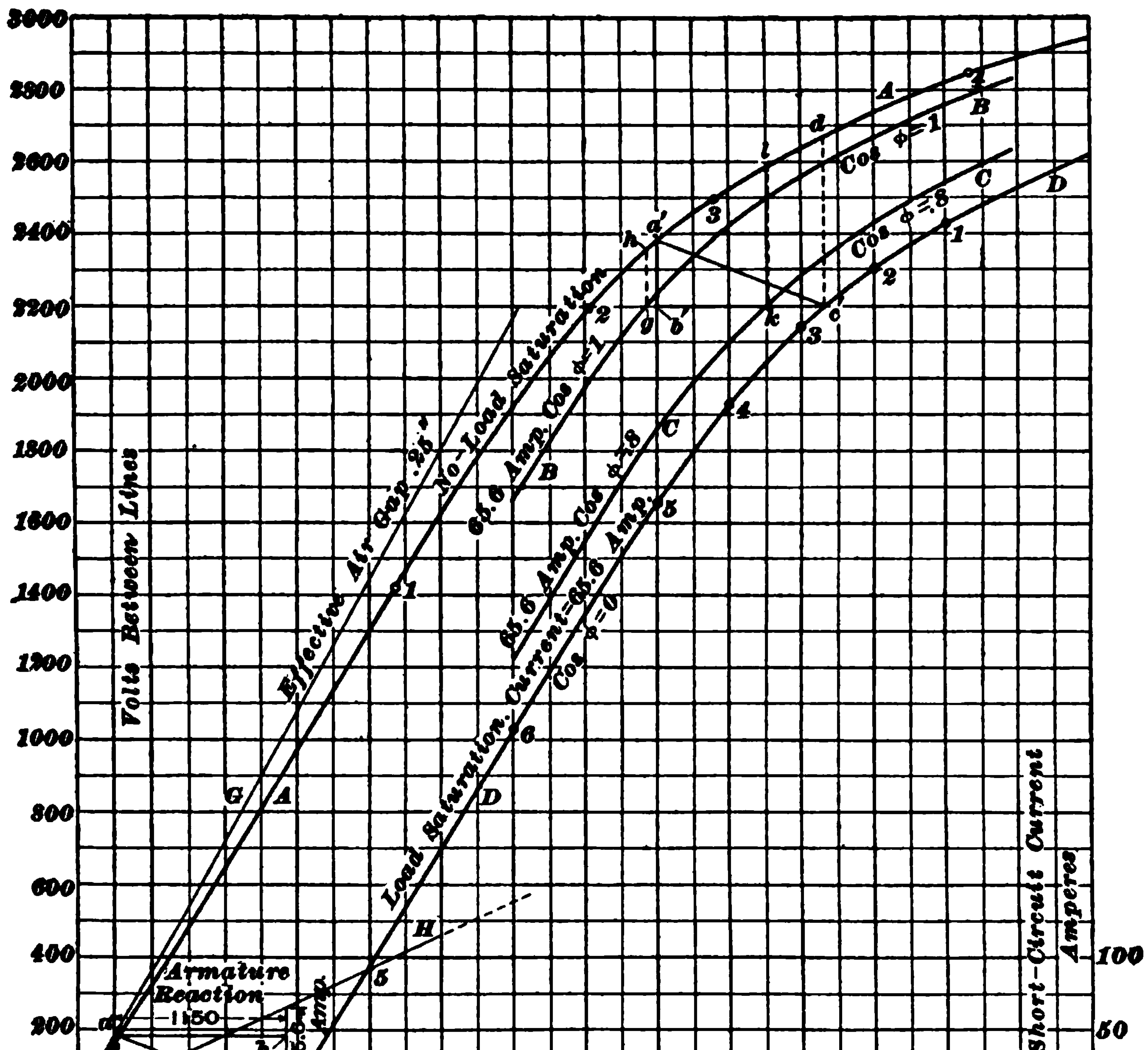
FIG. 5

21. Saturation Curve.—In order to obtain a **saturation curve** showing the relation between field ampere-turns and volts generated, it is sufficient to assume four fluxes and calculate the corresponding ampere-turns. The ampere-turns per inch for the various parts will be obtained from the curves shown in Fig. 5, which are here repeated for convenient reference.

TABLE I

CALCULATIONS FOR SATURATION CURVE

Useful Flux per Pole, Φ		1,000,000	1,540,000	1,750,000	2,000,000
Volts per phase, $E = \frac{4.44\ \Phi \times 320 \times 60}{10^8} \times .965$		823	1,267	1,440	1,645
Terminal volts, $\sqrt{3}\,E$		1,425	2,194	2,494	2,849
Leakage flux, $\Phi_l = 130.4\,X$ . .		257,000	396,000	450,000	514,000
Total flux, $\Phi + \Phi_l$		1,257,000	1,936,000	2,200,000	2,514,000
Air gap = .5 inch	$B = H$	25,200	38,800	44,100	50,300
$IT = .5 \times .313\,B$	$IT = 2\,X$	3,945	6,070	6,900	7,890
Teeth	B	69,000	106,000	121,000	138,000
(Length of path,	IT per in.	21	92	240	585
2.875 inches)	IT	60.4	264.5	690	1,682
Armature core . . .	B	22,100	34,000	38,600	44,200
(Length of path,	IT per in.	7.5	9.5	10	11
8.75 inches)	IT	65.6	83.1	87.5	96.3
Pole shoes	B	30,600	47,200	53,600	61,200
(Length of path,	IT per in.	9	12.5	14	17
1.125 inches)	IT	10.1	14.1	15.8	19.1
Pole cores	B	59,400	91,500	104,000	118,000
(Length of path,	IT per in.	16	45	85	210
11.5 inches)	IT	184	518	978	2,420
Spider rim	B	31,400	48,400	55,000	62,900
(Length of path,	IT per in.	12	18	19.5	24
6 inches)	IT	72	108	117	144
Total ampere-turns per pair of poles		4,337	7,058	8,788	12,321



Volts Between Lines
Effective Air Gap .25"
No-Load Saturation
65.6 Amp. Cos φ=1
65.6 Amp. Cos φ=.8
Load Saturation. Current=65.6 Amp. Cos φ=0
Armature Reaction
1150
65.6 Amp.
Ampere-Turns per Pole
Short-Circuit Current Amperes
Cos φ=1
Cos φ=.8
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
50
100

FIG. 6

Table I gives the ampere-turns required for the various parts with assumed fluxes of 1,000,000, 1,540,000, 1,750,000, and 2,000,000 lines per pole. For the flux of 1,540,000 lines, the terminal electromotive force is slightly under 2,200 volts; this is due to the fact that the actual number of turns per phase was taken slightly less than the calculated number, in order to make the number of turns divisible by the number of slots. In Fig. 6, the values given in Table I are plotted with ampere-turns per pole as abscissas and volts between lines as ordinates. Points *1*, *2*, *3*, and *4* are the calculated points, and a smooth curve *A A* is drawn through them. The calculated ampere-turns in the last line of Table I are ampere-turns per pair of poles, but it is usual to plot saturation curves in terms of ampere-turns per pole, or amperes, in case the number of turns per pole are known; hence, in Fig. 6 the ampere-turns corresponding to each of the calculated points are one-half the number in the last line of Table I. For example, point *2* is for 2,194 volts, and $7{,}058 \div 2 = 3{,}529$ ampere-turns per pole. About 3,550 ampere-turns per pole are required for normal 2,200 volts on open circuit.

Straight line *G*, Fig. 6, shows the relation between the line volts and ampere-turns required for the single effective air gap of .25 inch, and the ampere-turns included between line *G* and curve *A A* are the ones required for the iron part of the magnetic circuit. As the teeth and field cores become saturated, and their reluctance increased, curve *A A* deviates more widely from the gap line.

REGULATION

22. Before going on with the design of the field, it will be well to calculate the approximate regulation of the machine, in order to find out whether it comes within the specified limits of 8 per cent. on load of unity power factor and 20 per cent. on load of power factor .8. To ascertain the regulation, the short-circuit characteristic must first be drawn.

23. Short-Circuit Current.—The direction of the short-circuit line H, Fig. 6, is found by means of the formula previously given.

$$I_f T_f = k_c m I_p T_{pp}$$

from which
$$I_p = \frac{I_f T_f}{k_c m T_{pp}}$$

$I_f T_f$, the field ampere-turns per pole, may be taken as any convenient number, say, 2,000; k_c, as determined by tests on other similar machines, may be taken as .9; m, the number of phases, is 3; T_{pp}, the number of armature turns per pole per phase, is 8; and the short-circuit armature current

$$I_p = \frac{2{,}000}{.9 \times 3 \times 8} = 92.6 \text{ amperes, nearly}$$

In Fig. 6, lay off point *5* above 2,000, so that the ordinate will represent 92.6 amperes, to any convenient scale, such as that shown at the right-hand side of the figure. (One division is equal to 25 amperes short-circuit current.) Draw line *0 H* through point *5*, thus fixing the line that shows the relation between field ampere-turns and short-circuit current. This line shows that in order to make normal full-load current (65.6 amperes) flow in the armature, about 1,425 ampere-turns per pole are required, as indicated by the point c, the ordinate between c and the short-circuit line representing 65.6 amperes. The saturation curve for any power factor and full-load current therefore starts from point c. Of this 1,425 ampere-turns, the greater part is required to counterbalance the armature demagnetizing ampere-turns, and the remainder sets up the electromotive force that forces the current through the armature.

24. Armature Demagnetizing Ampere-Turns. The **armature demagnetizing ampere-turns** are found by means of the formula previously given.

$$\text{Demagnetizing ampere-turns per pole} = .9\, m\, T_{pp}\, I_p\, k_w\, k_p \sin a$$

Where m, the number of phases, is 3; T_{pp}, the number of turns per phase, 8; I_p, the current per phase, 65.6 amperes; k_w, for a three-phase winding with two slots per pole per

phase, .965; k_p, for the ratio $\frac{\text{pole arc}}{\text{pole pitch}} = \frac{4.4375}{7.07} = .628$, is .84; and, since the current will lag nearly 90° behind the induced electromotive force, sin a, at zero power factor, may be considered as 1. Therefore,

$$\text{demagnetizing ampere-turns} = .9 \times 3 \times 8 \times 65.6 \times .965 \times .84 = 1{,}150 \text{ ampere-turns, nearly}$$

Subtracting 1,150 ampere-turns $b\,c$, Fig. 6, from $O\,c$ leaves $O\,b$, or 275 ampere-turns effective in producing an electromotive force in the windings. The electromotive force required to force 65.6 amperes through the armature is therefore $a\,b$, or about 180 volts. By moving point a of triangle $a\,b\,c$ along $A\,A$ and keeping side $b\,c$ horizontal, point c will trace the load saturation curve $D\,D$ for a constant current of 65.6 amperes on zero power factor. This crosses the 2,200-volt line at c', and in order to maintain normal voltage with full-load current at zero power factor, about 5,150 ampere-turns per pole is required as against 3,550 on no load.

25. Regulation for Unity Power Factor.—Having obtained curve $D\,D$, Fig. 6, for zero power factor, curve $B\,B$ for full-load current (65.6 amperes) on unity power factor is drawn. The method of doing this was explained in detail in *Design of Alternating-Current Apparatus*, Part 1, so that it will not be necessary to repeat the steps here. Curve $B\,B$ crosses the 2,200-volt line at g, and to maintain this voltage when the machine is delivering 65.6 amperes to a load of unity power factor requires about 3,925 ampere-turns. If the field is excited to give this number of ampere-turns, and the load thrown off the voltage will rise by the amount $g\,h$, that is, from 2,200 volts to 2,360 volts, the rise in voltage is therefore 160 volts, and the regulation on full non-inductive load $160 \div 2{,}200 = .073$, or 7.3 per cent. This is within the specified limit of 8 per cent.

26. Regulation on Power Factor .8.—Curve $C\,C$, Fig. 6, is the load characteristic for power factor .8, drawn as already explained. This curve crosses the 2,200-volt line at k, where the excitation for full-load current is 4,760 ampere-

turns per pole. If, with this excitation, the load is thrown off, the voltage will rise the amount kl, that is, from 2,200 to 2,590 volts. The regulation for full-load current of 65.6 amperes at power factor .8 is therefore $390 \div 2{,}200 = .177$, or 17.7 per cent. This is within the specified limit of 20 per cent.

RESISTANCE OF ARMATURE

27. Before the resistance of the armature can be calculated, the armature coil must be laid out to scale and the mean length of an armature turn scaled off. Fig. 7 shows the shape of the coil, and the dotted line running through it indicates the average length of a turn. The coil pitch is from slot *1* to slot *7*; that is, one side of a coil is opposite the center of a north pole when the other side is opposite a south pole. The coils must be allowed to project well beyond the slots before they begin to bend, otherwise there will be danger of insulation breakdowns between the coil end connections and the core. The mean length of a turn, as scaled off from Fig. 7, is about 44.5 inches. By assuming the hot resistance of 1 mil-inch of copper to be 1 ohm, the resistance of the armature may be calculated from the formula

$$\text{hot resistance (ohms)} = \frac{\text{length in inches}}{\text{circular mils}}$$

There are 80 coils per phase with 4 turns per coil, the average length of the turns being 44.5 inches and the cross-section 49,000 circular mils; hence,

$$\text{hot resistance per phase} = \frac{44.5 \times 4 \times 80}{49{,}000} = .29, \text{ say } .3, \text{ ohm}$$

This makes a small allowance for the resistance of connections between coils and also for joints.

28. Ohmic Drop and Full-Load I^2R Loss.—With full load of 65.6 amperes, the IR, or ohmic drop, in each phase will be $65.6 \times .3 = 19.68$ volts, and the drop between terminals, $19.68 \times \sqrt{3} = 34$ volts, approximately.

At full load, the watts I^2R loss in each phase is $65.6^2 \times .3$, and this multiplied by 3 makes the total loss $65.6^2 \times .3 \times 3 = 3{,}870$ watts, approximately.

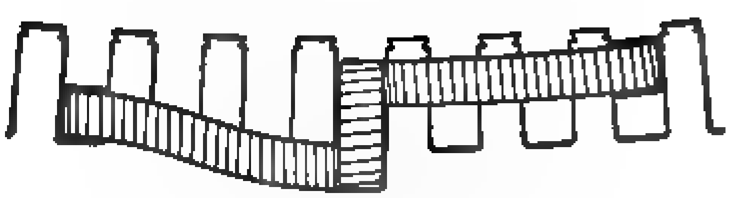


Fig. 7

DESIGN OF FIELD WINDING

29. From the saturation curve for zero power factor, 5,150 ampere-turns per pole is required to maintain the voltage under the most unfavorable conditions. However, in case the machine is overloaded, a considerably larger number of ampere-turns per pole will be needed. Calculations should therefore be made for placing a maximum of 7,500 ampere-turns, if possible, on each pole. The maximum excitation voltage with all resistance cut out of the rheostat in series with the field is 125, and the field winding must be designed so that it will not overheat when this voltage is applied. The assumed limit of the allowable temperature rise of 40° C. applies, however, only to full non-inductive load, so that it will not be necessary to keep within that limit on overloads at zero power factor.

30. Allowable Watts per Square Inch of Field-Coil Surface.—The outside diameter of the field is $90 - 2 \times .2 = 89.6$ inches, and the speed 180 revolutions per minute; hence, the peripheral speed is

$$\frac{89.6 \times 3.1416}{12} \times 180 = 4{,}225 \text{ feet per minute, nearly}$$

From *Design of Alternating-Current Apparatus*, Part 1, it is found that for a peripheral speed of 4,000 feet per minute, 2.5 watts per square inch can be dissipated with a rise in temperature of 40° C. At a speed of 5,000 feet per minute, 2.9 watts can be dissipated. For 4,225 feet per minute, approximately 2.6 watts per square inch can be dissipated.

31. Field Winding.—To determine the mean length of a field turn, the breadth of the edgewise-wound strip may be assumed to be $\frac{3}{4}$ inch. Laying out a section of the field core as shown in Fig. 8 and allowing $\frac{1}{8}$-inch clearance at the sides for insulation, the mean length of a turn, as indicated by the dotted line, is found to be 24.4 inches. For narrow coils like this it is customary to make the ends of the coil semicircular, as they are easily bent to this form.

With 125 volts applied to the whole winding made up of 40 coils connected in series, the pressure across the terminals of each coil will be $125 \div 40 = 3.1$ volts. The hot resistance r per field coil is $\frac{l\,T}{\text{c. m.}}$, where l is the mean length of a turn of field copper in inches, T the number of turns per

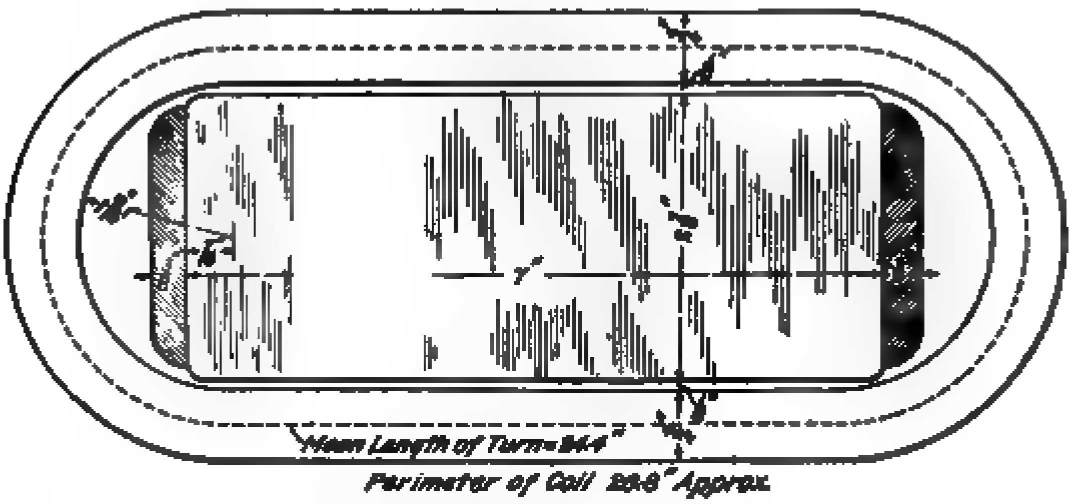


FIG. 8

coil, and c. m. the circular mils cross-section. The field current is $\frac{e}{r} = \frac{e \times \text{c. m.}}{l\,T}$, where e is the volts per coil; hence, the ampere-turns per coil,

$$I_f\,T_f = \frac{e \times \text{c. m.} \times T}{l\,T} = \frac{e \times \text{c. m.}}{l}$$

or, $$\text{c. m.} = \frac{I_f\,T_f\,l}{e} = \frac{7{,}500 \times 24.4}{3.1} = 59{,}000$$

Square mils = 59,000 × .7854 = 46,400, approximately

The strip is $\frac{3}{4}$ inch, or 750 mils, wide, and if it is made $\frac{1}{16}$ inch, or 62.5 mils, thick, it will have a cross-section of 750 × 62.5 = 46,875 square mils.

The outside perimeter of the coil is 26.8 inches. The pole cores are $5\frac{3}{4}$ inches long, radially, and allowing $\frac{1}{2}$ inch for the two insulating end collars, the space occupied by the coil will be $5\frac{1}{4}$ inches. Assuming for the present that the coil fills this space, its radiating surface is 26.8 × 5.25 square inches, and the allowable watts per spool is 26.8 × 5.25 × 2.6 = 366 watts.

The pressure across the coil terminals is 3.1 volts; hence, the allowable field current for 40° C. rise in temperature is $366 \div 3.1 = 118$ amperes.

Since there are to be 7,500 ampere-turns supplied by each spool, the active number of turns per spool is $7{,}500 \div 118 = 63.56$. In order to connect the coils on the machine conveniently, the terminals must come out on opposite sides, thus necessitating a half turn more than a whole number. The number of active turns may then be $63\frac{1}{2}$, $64\frac{1}{2}$, or $65\frac{1}{2}$; $65\frac{1}{2}$ turns will be used, and room must be allowed for 66 thicknesses of copper and 65 layers of .012-inch insulating paper for separating the turns. The total height of coil will be $66 \times .0625 + 65 \times .012 = 4.9$, say 5, inches. The available space is $5\frac{1}{4}$ inches, so that the poles can be shortened $\frac{1}{4}$ inch, thus making the final dimensions of the poles and field rim as shown in the small circles, Fig. 4. Since the winding does not present quite as large a surface as figured on, the watts per square inch will be a little over 2.6, but not enough to make it necessary to redesign the winding. The temperature rise of 40° C. assumed at the outset applies only to full non-inductive load, while the calculations just made are for a highly inductive overload. If such a condition should arise, the field coils can easily withstand, without injury, a temperature rise slightly over 40° C.; on full non-inductive load, the rise will be considerably below the specified limit.

If it were necessary to keep below 40° rise under the most unfavorable conditions, the poles could be left $5\frac{1}{4}$ inches long and be filled with a winding capable of giving slightly over 7,500 ampere-turns per pole; but 7,500 should be ample for this machine, and there is no economy in putting in more material than is actually needed.

LOSSES AND EFFICIENCY

32. The electrical design of the machine has now been completed. The dimensions obtained, however, are by no means the only ones suitable for a machine of the specified speed, output, etc. Other machines built on different diameters might work equally well; in fact, a practical designer

would probably make calculations for a number of machines with different diameters and then use the design giving the best all-around results. Since all dimensions, magnetic densities, etc. are now known, the approximate losses in the various parts can be calculated and the efficiency determined.

CORE LOSSES

33. Loss in Teeth.—The teeth are .553 inch wide at the tip and .591 inch at the root (see Fig. 3). The average width of a tooth is .572 inch, the net length of iron in the core parallel with the shaft is 7.75 × .9, and the radial length of a tooth is 1.4375; then,

$$\text{volume of teeth} = .572 \times 7.75 \times .9 \times 1.4375 \times 240 = 1{,}378 \text{ cubic inches}$$

The density in the teeth at normal voltage is 106,000 lines per square inch and the core loss for this density at 60 cycles is about 3.55 watts per cubic inch (see *Design of Alternating-Current Apparatus*, Part 1); hence,

$$\text{loss in teeth} = 1{,}378 \times 3.55 = 4{,}892, \text{ say } 4{,}900, \text{ watts}$$

34. Loss in Armature Core.—The volume of the core under the teeth can be calculated as follows:

$$\text{Diameter of core at bottom of teeth} = 90 + 2\tfrac{7}{8} = 92.875 \text{ inches}$$

$$\text{Diameter of outside of core} = 92\tfrac{7}{8} + 2 \times 3\tfrac{1}{4} = 99.375 \text{ inches}$$

$$\text{Volume of core} = .7854\,(99.375^2 - 92.875^2) \times 7.75 \times .9 = 6{,}850 \text{ cubic inches, nearly}$$

The density in the core is 34,000 lines per square inch, which will make the loss about .36 watt per cubic inch, and

$$\text{loss in core} = 6{,}850 \times .36 = 2{,}466, \text{ say } 2{,}500, \text{ watts}$$

The total calculated iron loss will be 4,900 + 2,500 = 7,400 watts.

To make some allowance for high densities in the teeth, caused by field distortion when the machine is loaded, and also for some loss in the pole face, about 10 or 15 per cent. should be added, making the total iron loss due to hysteresis and eddy currents, say 8,400 watts.

Accurate core-loss calculations are very difficult to make, because poor iron, poor die work in making the punchings,

TABLE II

EFFICIENCY CALCULATIONS

Load Fractional Part of Full Load	Watts Output	Line Current	Armature I^2R Loss	Core Loss	Field Current	Field I^2R Loss	Total Loss	Input	Electrical Efficiency
$\frac{1}{4}$	62,500	16.4	240	8,400	55.65	3,280	11,920	74,420	84.
$\frac{1}{2}$	125,000	32.8	970	8,400	57.1	3,460	12,830	137,830	90.9
$\frac{3}{4}$	187,500	49.3	2,180	8,400	58.55	3,640	14,220	201,720	93.1
1	250,000	65.6	3,870	8,400	60.	3,820	16,090	266,090	93.8
$1\frac{1}{4}$	312,500	82.	6,050	8,400	61.45	4,010	18,460	330,960	94.4
$1\frac{1}{2}$	375,000	98.6	8,720	8,400	62.9	4,200	21,320	396,320	94.6

poor insulating varnish, etc. may cause the core losses to be much higher than calculated.

COPPER LOSS

35. Loss in Armature.—The **copper loss** in the armature will vary as the square of the current output. The resistance per phase has already been calculated and is .3 ohm; hence,

armature I^2R loss $= 3 \times .3 I^2 = .9 I^2$,

from which the loss is easily calculated for any given current.

36. Loss in Field. At no load, about 3,550 ampere-turns per pole is required, and as each pole has 65.5 turns, the field current at no load will be $3,550 \div 65.5 = 54.2$ amperes. At full noninductive load, 3,925 ampere-turns is required; hence, the field current will be $3,925 \div 65.5 = 60$ amperes. In other words, the field current must be

gradually increased from 54.2 amperes at no load to 60 amperes at full non-inductive load, an increase of 5.8 amperes. The field current for 125 volts applied electromotive force is 118 amperes; hence, the hot field resistance is 125 ÷ 118 = 1.06 ohms, and

$$\text{field } I^2 R \text{ loss} = 1.06\, I^2$$

It is safe to assume that the field current changes in direct proportion to the load; that is, it will be 54.2 amperes at no load, 57.1 amperes at half load, 60 at full load, 62.9 at 1½ load, etc., as given in Table II.

Table II also gives the losses and efficiencies at the various

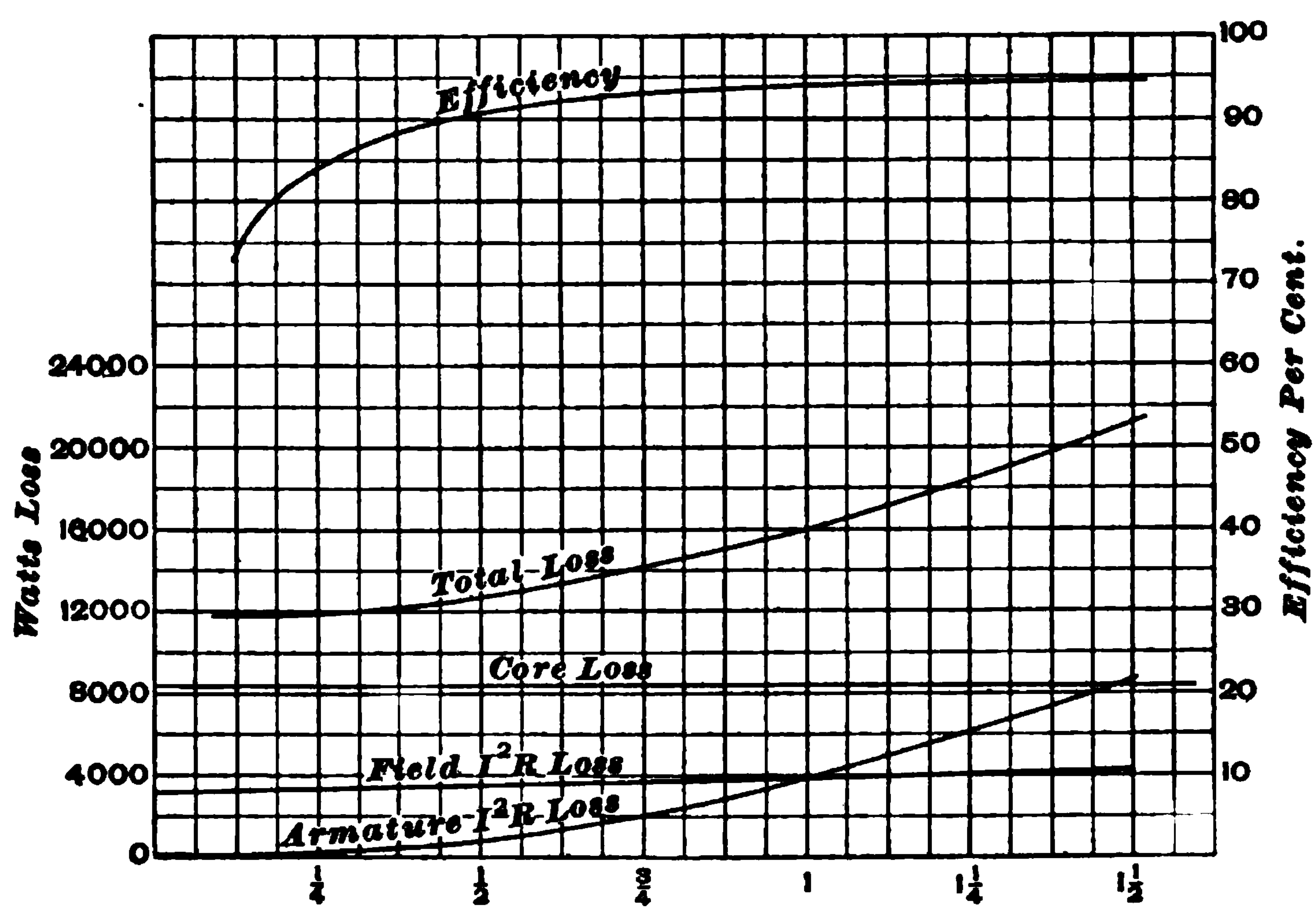
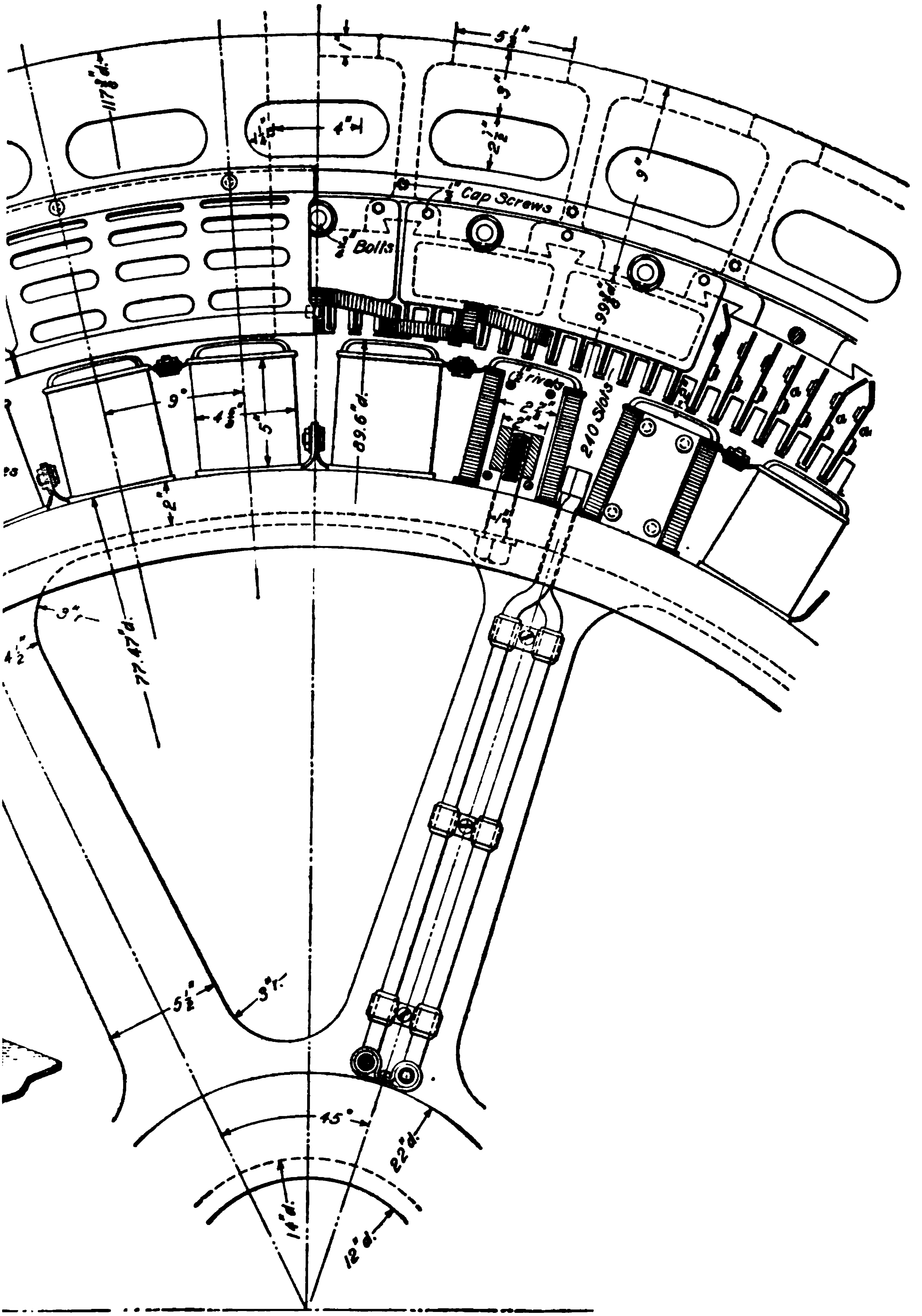


FIG. 9

loads, the efficiencies being calculated from a consideration of the electrical losses only. Windage and friction are not considered as part of the generator losses where the machine is direct-connected to the engine. The loss in the field rheostat has also been omitted, as it is not customary to include this loss in efficiency calculations.

The various losses and the efficiency are shown by the curves in Fig. 9. The efficiency is still rising slightly at 1½ load, but if the machine were loaded much beyond this

11½"


117⅞" d.
4"
5½"
3"
2½"
9"
½" Cap Screws
Bolts
99⅞" d.
240 Slots
89.6" d.
9"
5"
2"
77.47" d.
9" r.
4½"
5½"
3" r.
45°
22" d.
14" d.
12" d.

point the efficiency would decrease, owing to the large increase in the armature I^2R loss. The efficiencies are slightly higher than those required by the specifications.

ARMATURE HEATING

37. It is difficult to calculate the rise in temperature of the armature, because a great deal depends on the mechanical construction of the machine and the ease with which the air-currents can circulate around the core and windings. However, the I^2R loss per square inch of armature surface can be calculated and compared with the allowable loss for machines of similar design. As assumed at the start, the circular mils per ampere M_t in the armature conductors at full load are 750, and the ampere-conductors per inch periphery K are 450; by a formula previously given, watts I^2R loss per square inch of stator face,

$$W_t = \frac{K}{M_t} = \frac{450}{750} = .6$$

This is a conservative value, and the I^2R loss should not cause the machine to overheat. The whole construction of this generator is very open, on account of the large diameter of armature, and there should be no difficulty in carrying off all the heat with a rise in temperature not exceeding the specified 40° C.

MECHANICAL CONSTRUCTION

38. The **mechanical construction** of the alternator for which the calculations have been made is shown in Fig. 10, which, for the most part, is self-explanatory. The field spider is made of cast steel; it has eight arms, and would probably be cast in one piece with a split hub clamped to the shaft by four bolts. The poles are laminated, the punchings being held between the end heads by four rivets. The laminations have a square opening to receive a bar, into which the holding-on bolts are tapped. Current is conducted to the field coils by stranded rubber-covered cables, which

run down one of the spokes to the hub and thence along the shaft to the collector rings. These leads are held firmly in place by brass cleats screwed to the arm and provided with insulating bushings through which the cables pass. As this alternator is to be direct-connected to the engine, it should be provided with split collector rings that can be removed without disturbing the outboard bearing.

The armature laminations are clamped between segmental end plates, which are recessed so as to reduce the weight. The ventilating ducts are formed by iron spacing strips *a*, which are fastened to the punchings so as to stand on edge. The yoke is provided with cored openings, to allow free circulation, and the winding shields are also made as open as possible.

There are various ways of fastening the ventilating spacers. Those shown in Fig. 10 are represented more clearly in the detail sketch. The spacer *a*, which is punched from heavy sheet metal, has two lugs *b* projecting on opposite sides and some distance apart. The heavy supporting punching on the side of the air duct has two raised parts *c*, which are made by slitting and punching out the parts with a die. After the lugs on the spacer are in place, the raised parts are swaged down, thus locking the spacer securely in place. On heavy stampings, some manufacturers rivet ribs each side of the air duct, others use brass castings similar in general shape to an armature segment, but with spacing ribs, etc.

INDUCTION MOTORS

39. An induction motor is a machine for transforming electrical energy into mechanical energy; it consists of a magnetic field excited by an alternating current, and an armature in which alternating current is induced by the rotating magnetism of the field, mechanical energy being delivered at the pulley. Either the field or the armature may be fixed in position, the other rotating, but in the following discussion it will be considered that the field is fixed and that the armature rotates. In many respects, an induction motor resembles a transformer, the primary winding of which is on the field and the secondary winding on the armature; hence, the field of an induction motor is frequently called the *primary*, and the armature is referred to as the *secondary*. The essential difference between an induction motor and a transformer is that in the motor one winding is free to rotate, and in the transformer both windings are fixed. A transformer supplied with a constant primary pressure will furnish nearly a constant secondary pressure independently of the load; an induction motor when supplied with a constant primary pressure will run at nearly a constant speed independently of the load. The energy developed in the secondary winding of the induction motor is expended in causing rotation and supplying mechanical energy, instead of causing heat and light in an external circuit, as is the case with an ordinary transformer.

GENERAL OPERATION

CIRCLE DIAGRAM

40. When an induction motor is connected to the mains and allowed to run idle without any load other than its own friction, it runs at a speed nearly equal to that of synchronism; that is,

$$\text{revolutions per minute} = \frac{120n}{p},$$

in which n = frequency (cycles per second);

p = number of poles for which the stator is wound.

When running this way, the motor will take a comparatively large current from the line, considering the fact that no load is being carried; the no-load, or so-called *magnetizing current*, may be from 25 to 40 per cent. of the normal full-load current of the motor. However, this current lags greatly behind the electromotive force and does not therefore represent much power, since the power factor is low. The actual power supplied is that required to supply the losses in the motor, consisting of core loss, I^2R loss in stator and rotor, and friction and windage.

As the load is applied to the motor, the current taken from the line will gradually increase and its lag behind the electromotive force will decrease. The power factor therefore increases with increasing load. To determine the power factor corresponding to a given load, it is necessary to connect watt meters to the primary; their readings give the true watts supplied, which, divided by the volt-amperes as obtained from ammeter and voltmeter readings, give a power factor equal to cos ϕ, in which ϕ is the angle by which the current lags behind the applied electromotive force.

41. In Fig. 11, the vertical line OE' represents the direction of the applied electromotive force, that is, the pressure between motor terminals. Lay off OA to represent the no-load primary current to any convenient scale, making angle ϕ equal to the angle of lag as calculated from the

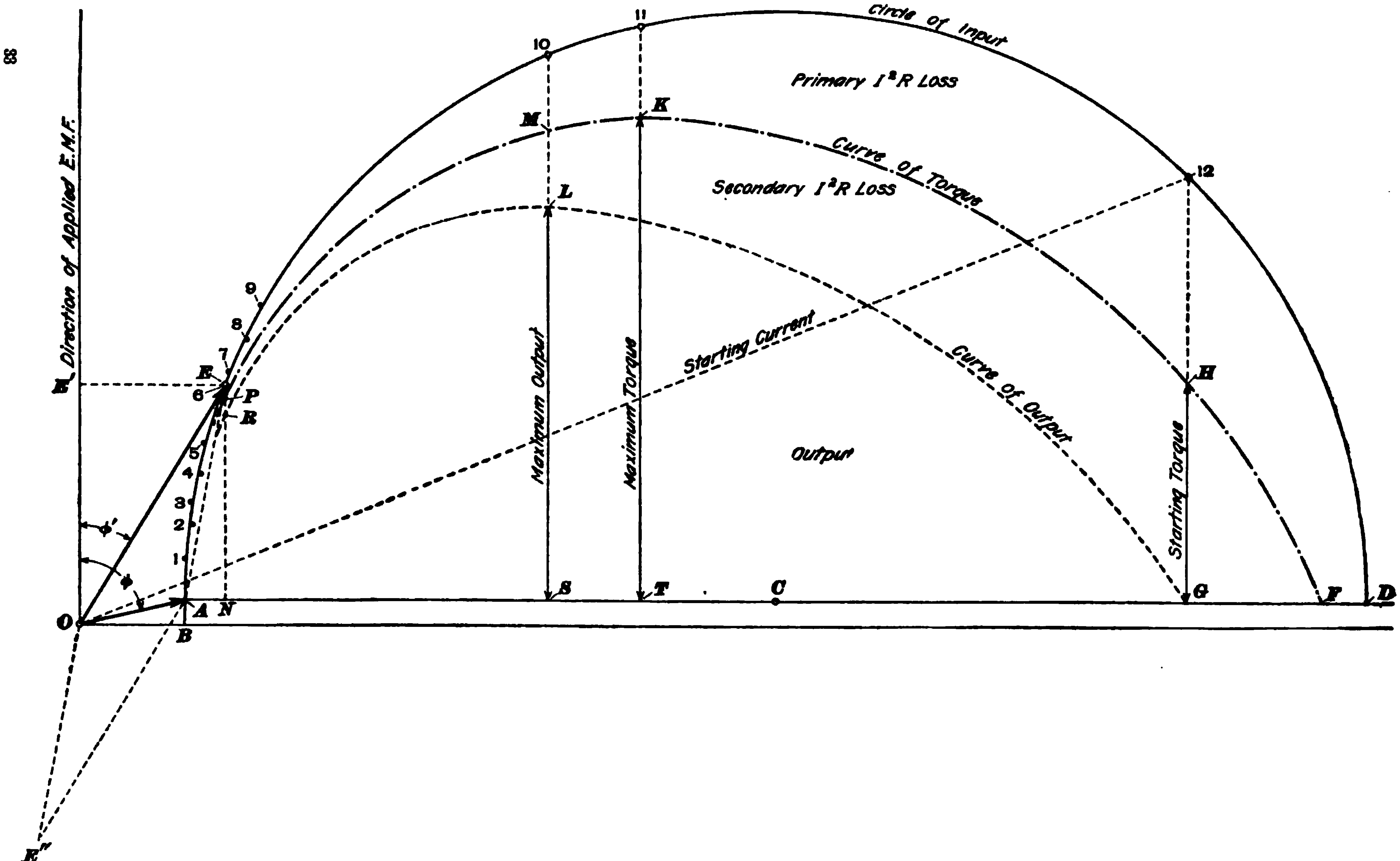

Circle of Input
Primary I^2R Loss
Curve of Torque
Secondary I^2R Loss
Starting Current
Curve of Output
Output
Maximum Output
Maximum Torque
Starting Torque
Direction of Applied E.M.F.
O
A
B
N
S
T
C
G
F
D
E
P
R
L
M
K
H
E''
1
2
3
4
5
6
7
8
9
10
11
12
ϕ
ϕ'

Fig. 11

wattmeter, ammeter, and voltmeter readings. This angle will be quite large, and the power factor correspondingly low. The no-load current OA can be considered as made up of two components, one OB at right angles to OE' and the other BA parallel with OE'. OB is the component required to set up the magnetic flux through the motor, and is, therefore, the true magnetizing current; it is much larger than the magnetizing current in a transformer, because the motor has an air gap between stator and rotor, across which the flux must be forced. AB, the watt component of the no-load current, is the part in phase with the electromotive force, and represents the actual power used to make up the no-load losses; these losses remain practically constant at all loads. In practical calculations, the no-load current is often called the magnetizing current, that is, OA and OB are considered equal.

42. As the load on the motor is increased and readings of the instruments taken for each successive load, points *1*, *2*, *3*, etc., Fig. 11, can be located, because in each case the direction of lines joining these points to O is determined by the calculated angle of lag, while the distances of the points from O are laid off to represent the various currents, to the same scale that OA represented the no-load current. In the figure, all these lines, except the full-load line, have been omitted so as not to make the diagram confusing. If point *6*, or E, is the end of the full-load line, OE represents the full-load current and ϕ' the full-load angle of lag, $\cos\phi'$ being the full-load power factor. The watt component of the full-load current is OE'. As the load is increased beyond full load, points *7*, *8*, and *9* are obtained. It has been found that all these points lie on a semicircle, having its center C on the horizontal line passing through A, the extremity of the no-load current line.

The fact that these points lie on a semicircle has been demonstrated mathematically by Heyland, Behrend, Bedell, and others. The theory was first made public by Heyland and the diagram is frequently called the *Heyland circle*

diagram. Tests on induction motors bear out the theory with remarkable closeness. The proof is beyond the scope of this treatise, but those interested will find it in the works of Behrend, La Tour, and others. The diagram is exceedingly important in the study of induction motors, and many different forms of it have appeared. The one here given has been simplified as much as possible, and in doing so some approximations have been introduced. However, the diagram applies quite closely to motors of over 5 horsepower output, and aids in explaining the action of induction motors under various loads.

43. The magnetizing current OA, Fig. 11 (OA and OB being considered equal—see Art. **41**), remains nearly constant for all loads, and its direction may, without any great inaccuracy, be taken the same for all loads. The primary and secondary currents combined always give OA as a resultant; that is, OA is the diagonal of the parallelogram $OEAE''$, and OE'' is the direction of the secondary current. But $OE'' = AE$, and to obtain a proportional value of secondary current corresponding to a given current in the primary, it is simply necessary to join the point on the circle corresponding to the primary current to A. Thus, if OE is the primary current at full load, then AE represents, proportionally, the corresponding secondary current. The actual current in the secondary would be the number of amperes represented by AE multiplied by the ratio of the number of primary conductors to the number of secondary conductors. Usually, the rotor has comparatively few conductors; therefore, in order to ascertain the current in the secondary, AE must always be multiplied by the ratio of transformation of the motor. The secondary-current line AE is usually from 6 to 20 per cent. shorter than the full-load primary-current line, because the primary current includes the magnetizing component.

At full load, the total number of watts supplied to the motor is proportional to OE', which is the power, or watt, component of the current. Of this, the core loss, friction, etc.

is represented by AB; that is, $EN = (OE' - AB)$ is proportional to the total number of watts less the no-load losses; and of EN, part is lost in the windings, due to I^2R losses in primary and secondary. If from EN part EP, representing the I^2R loss in the primary, is subtracted, the remaining part PN will represent the power transferred from the stator to the rotor through the medium of the rotating magnetic field. Of this power, part is lost in the rotor windings; hence, subtracting PR, representing the rotor I^2R loss, leaves RN as the output of the motor. At full load and at lower loads, the I^2R losses are comparatively small, as shown by the short lengths of EP and PR. At large currents, however, for example, that corresponding to point *10*, the losses become much exaggerated, as indicated by *10*–M and ML.

44. If the input circle AED, Fig. 11, and the resistance of the stator winding are known, the primary I^2R loss for different points on the curve may be calculated and the dot-and-dash curve PKF may be so drawn that the ordinates between it and the input circle will represent the primary I^2R loss for each point. Thus, *10*–M is proportional to the primary I^2R loss corresponding to primary current *O–10*. In the same manner, the dotted curve RLG can be drawn so that the ordinates between it and the dot-and-dash line represent the secondary I^2R loss; for example, ML is proportional to the secondary I^2R loss due to a secondary current proportional to A–*10*. The ordinates between the dotted curve RLG and the horizontal line AD represent the outputs for different primary currents; hence, curve RLG may be called the *curve of output.*

The torque, or twisting effort, exerted by the rotor depends on the input that the rotor receives through the medium of the magnetic field; hence, the torque is proportional to the ordinates between curve PKF and the horizontal line AD; thus, PN is proportional to the full-load torque, and RN to the full-load output. Curve PKF may therefore be called the *curve of torque.*

45. As the load on the motor is increased, the primary current becomes greater, and the torque and output also increase until a maximum is reached. For the current *O–10*, the maximum output LS is attained, and at current *O–11* the maximum torque KT is reached. If the motor load is increased, so that a torque greater than the maximum KT is required, the motor will stop, and a current represented by the line *O–12* will flow through the primary winding, causing losses $12\text{–}H + HG + AB$. The current never reaches point D, this being the theoretical limit if the windings of the motor had no resistance.

46. Starting Torque and Current.—The current at standstill, *O–12*, is the starting current that would flow through the primary winding of the motor if full voltage were impressed on it; the secondary starting current is proportional to a line *A–12*. With these starting currents, the **starting torque** is HG, because HG represents the input into the rotor. The proportions of Fig. 11 are approximately such as would be obtained from a test on a motor with a squirrel-cage rotor, and it is at once seen that even with the abnormally large starting current *O–12*, in this case over four times full-load current OE, only a very moderate starting torque HG is obtained. The full-load running torque is PN, and this is only very slightly exceeded by HG, notwithstanding the large starting currents in stator and rotor. This comparatively low starting torque is due largely to magnetic leakage, which is much more pronounced in an induction motor than in an ordinary transformer. The flux that actually enters the rotor is so modified in its amount and phase relation to the secondary current that the torque per ampere is very much less than under normal running conditions.

47. Use of Starting Resistance.—The abnormally large currents at starting can be reduced by inserting **resistance** in the secondary circuit. This makes the starting torque line, Fig. 11, longer, because the I^2R loss for a given current in the secondary circuit is increased. Points H

and *12* are thus shifted back to higher parts of the curves, and if the resistance is large enough, the end of the starting-current line may be brought around to point *11*, thus making the starting current *O–11* instead of *O–12*, and the starting torque KT instead of HG. Thus, the insertion of secondary resistance at starting not only reduces the starting current, but also gives a much greater starting torque. If necessary, the resistance can be made large enough to bring the end of the starting-current line around to point E, thus making the motor start with full-load torque and normal full-load current. In order that the excessive secondary I^2R loss may continue only while the motor is starting, the resistance must be arranged so that it can be cut out as the motor comes up to speed; this necessitates slip rings and sacrifices the simplicity of the squirrel-cage construction.

With a squirrel-cage motor, a large starting torque with moderate current cannot be obtained unless the resistance of the bars or end rings is made high; and from the nature of the squirrel-cage construction, this resistance is permanently in the rotor. This makes the rotor I^2R losses high, reduces the efficiency of the motor under regular running conditions, and makes the speed regulation poor.

48. Slip.—The difference between synchronous, or no-load, speed and full-load speed is called the **slip**, which is usually expressed as a percentage of synchronous speed. The percentage slip is almost exactly equal to the percentage I^2R loss in the secondary; for example, a motor having a slip of 3 per cent. at full load would have approximately 3 per cent. of the motor output lost in the secondary windings. If a squirrel-cage winding is made of high resistance, in order to secure good starting torque, it follows that the slip will be large and the speed variation from no load to full load correspondingly great. The maximum output of the motor is cut down, because the I^2R losses in the secondary are increased.

49. Motors for Large Starting Torque.—For certain classes of work, such as elevator and crane service, high

resistance squirrel-cage rotors have been used to some extent, because the service is intermittent and the low efficiency is not very objectionable. In such rotors, high resistance is usually secured by making the short-circuiting rings of low-conductivity metal; if the load remains on long, the rings get very hot, making them unsuitable for continuous service.

If a large starting torque is required, or if the starting current must be limited to avoid an undesirable effect on the voltage regulation of the supply circuit, it is necessary to use a Y-wound rotor with the terminals connected either to slip rings, for the insertion of an external resistance, or to a resistance mounted on the armature spider and arranged so that it can be cut out when the motor has attained speed.

50. Power Factor.—Referring to Fig. 11, with a given watt component AB, the shorter the no-load current line OA and the larger the diameter of the circle, the less the values of angle ϕ for corresponding load points. In other words, the smaller the no-load current of a motor and the larger the diameter of its circle diagram, the less will be the angle of lag at any given load or the higher the power factor. The no-load current OA depends very largely on the clearance between stator and rotor, on the kind of slots (whether open or closed), and on the magnetic density in the air gap. The air gap cannot be made less than the limits fixed by mechanical requirements, while the air-gap density is limited by the allowable density in the stator teeth. The magnetizing current cannot therefore be reduced below a certain point, and is seldom less than 20 per cent. of full-load current. The maximum power factor is obtained when the load current line (OE for full load) becomes tangent to the circle, and it is desirable to have this occur at about three-quarter load, because, as a rule, the average load on a motor will be more nearly three-quarter load than full load.

51. Leakage Factor, or Dispersion Coefficient. The diameter of the circle, Fig. 11, has been found to be equal to the magnetizing current OB divided by a number

known as the **leakage factor, or dispersion coefficient,** of the motor; that is,

$$\text{diameter of circle} = \frac{\text{magnetizing current}}{\text{leakage factor}} \qquad (1)$$

and

$$\text{leakage factor} = \frac{\text{magnetizing current}}{\text{diameter of the circle}} \qquad (2)$$

The leakage factor takes into account the stray leakage, or dispersed magnetic field, surrounding the primary and secondary conductors. The larger the dispersion, the greater will be the reactance of the windings and the larger the leakage factor.

As is evident from formula **1**, a large leakage factor with a given magnetizing current makes a small diameter of circle and consequently a low power factor.

52. Many formulas have been devised for calculating the leakage factor, because if this can be determined, the circle can be laid out and the complete performance of the motor can be predicted. The leakage factor may be found from a test on a completed motor by first determining the circle. This can be done by locating any two or more points. For example, the no-load current and the current with the rotor locked, with the angle of lag in each case, are easily measured; these give the data for locating points *A* and *12*. The circle must have its center on the horizontal line through *A* and must pass through points *A* and *12*. The determination of a third point, for instance, the full-load current and its angle of lag, locating point *6*, will serve as a check on the first two measurements, for all the points should come on the circle. The circle being determined, the leakage factor is the ratio $\frac{OB}{AD}$.

The formulas that have been proposed for calculating the leakage factor are necessarily complicated, because the factor depends on the size and shape of the slots, length of the air gap, pole pitch, length of the coil end connections, and a number of other things more or less difficult to estimate accurately. The result is that the complicated formulas

seldom give any closer results than more simple ones deduced from tests on motors. The simplest formula is one given by B. A. Behrend, and is as follows:

$$\text{leakage factor} = \frac{\text{air gap}}{\text{pole pitch}} \times C,$$

where C is a coefficient that, except for very small motors, is seldom over 20 and is not often less than 10, even in large motors.

For a given type of motor, a designer can usually approximate C with a fair degree of accuracy and thus obtain a reasonably close value of the leakage factor. The aim is always to keep the leakage factor as low as possible, and the formula shows that a large pole pitch and a small air gap are desirable. With a given frequency, a large pole pitch is accompanied by a correspondingly high peripheral speed, and this sometimes limits the pitch that can be used. In most cases, the leakage factor lies between .03 and .08, the lower limit being attained only in motors with unusually favorable conditions.

STATOR WINDINGS

53. The **stator winding** for a polyphase induction motor is similar to that for a polyphase alternator. Windings may be of the chain or the two-layer type, the latter being generally used unless the motor is wound for high potential. Usually, induction-motor windings have more slots per pole per phase than alternators, as experience has shown that a large number of slots is desirable. The principles governing the arrangement of the coils and their connections, however, are exactly the same as for alternators, and the statements in regard to the effect of distributing the windings apply with equal force to induction motors.

54. Electromotive-Force Formulas.—Since induction-motor windings are seldom distributed in less than three slots per pole per phase, and usually in four or more, it is accurate enough to take the distribution factor as .95 for all three-phase motors. The winding must be designed

so that, neglecting the small ohmic drop, it will set up a counter electromotive force equal to the applied line electromotive force.

For three-phase motors,

$$E_p = \frac{4.44\,\Phi\,T_p n}{10^8} \times .95$$
$$= \frac{4.2\,\Phi\,T_p n}{10^8}, \qquad (1)$$

in which E_p = volts applied to one phase;
T_p = turns per phase;
Φ = flux per pole;
n = frequency (cycles per second).

For two-phase motors a fair value of the distribution factor will be .9, and

$$E_p = \frac{4.44\,\Phi\,T_p n}{10^8} \times .9$$
$$= \frac{4\,\Phi\,T_p n}{10^8} \qquad (2)$$

By substituting a constant k for the value 4.2 for three-phase motors and 4 for two-phase motors, the formula becomes general. Thus,

$$E_p = \frac{k\,\Phi\,T_p n}{10^8} \qquad (3)$$

MAGNETIC FIELD AND MAGNETIZING CURRENT

MAGNETIC FIELD

55. If the stator windings of an induction motor were distributed in a large number of slots, the field at a given instant would be distributed somewhat as shown in Fig. 12. This magnetic field is constantly rotating, but at any instant it consists of a number of poles, depending on the winding. The field shown has six poles, and the magnetic density is greatest opposite the center of the poles and shades off toward each side, according to the sine law. For example, considering

two poles NS, Fig. 13, if the maximum magnetic density is $\mathbf{B}_{max.}$, the average density $\mathbf{B}_{av.}$ will be

$$\mathbf{B}_{av.} = \mathbf{B}_{max.} \times \frac{2}{\pi} = \mathbf{B}_{max.} \times .636$$

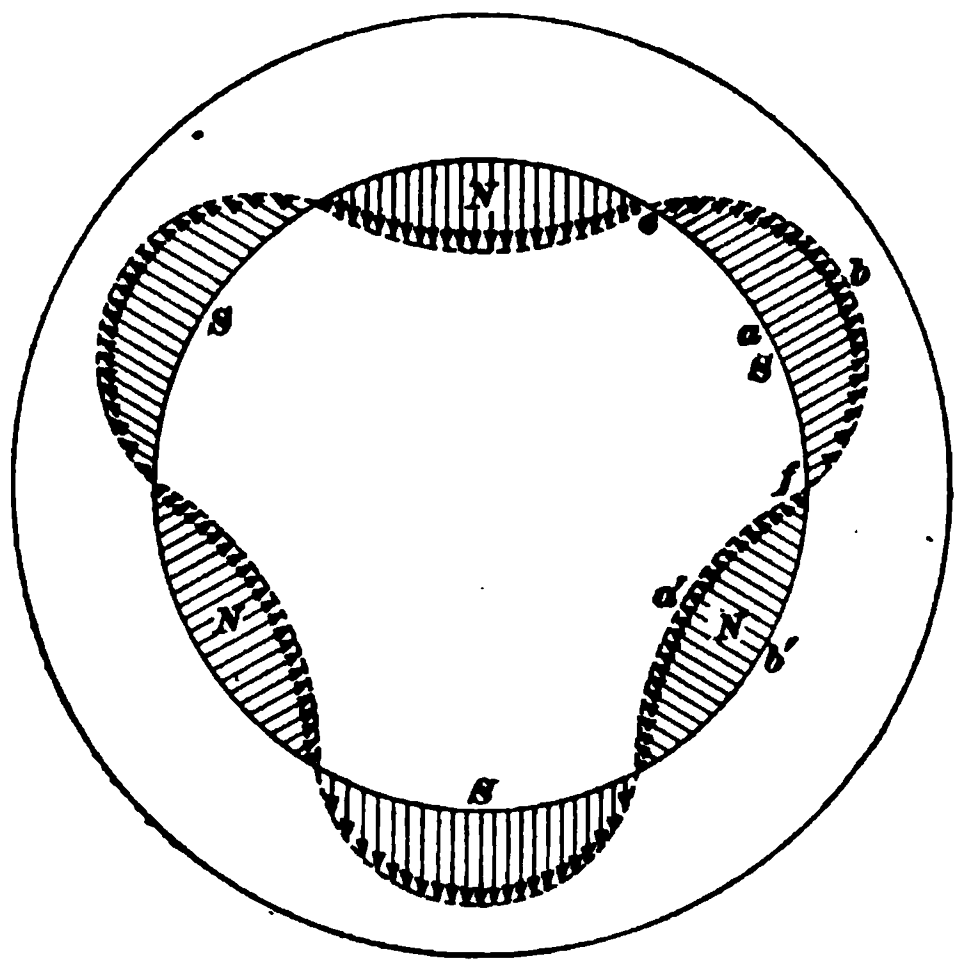


FIG. 12

If T is the pole pitch, or distance between pole centers, and l the length of the core measured parallel with the shaft,

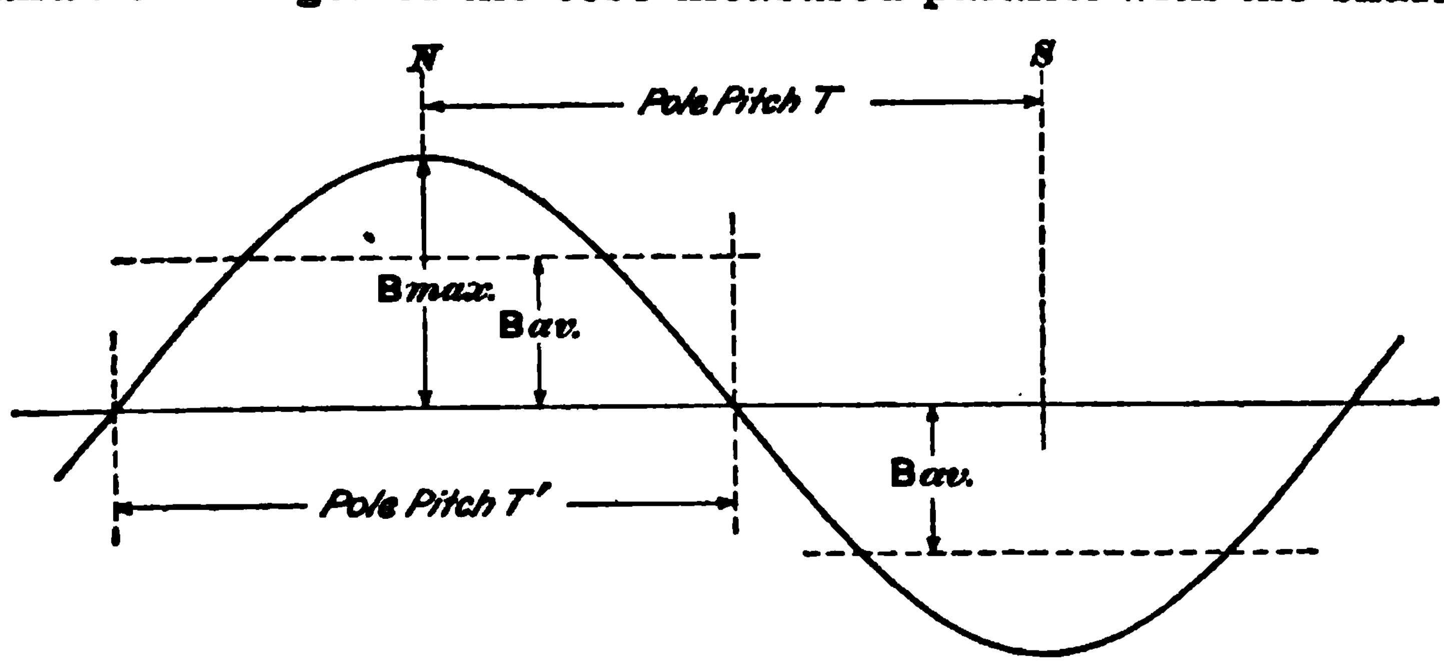


FIG. 13

then Tl is the polar area and the flux through the pole is

$$\Phi = Tl\,\mathbf{B}_{av.}$$
$$= .636\,Tl\,\mathbf{B}_{max.}$$

where Φ is the total number of lines per pole.

In induction motors there are from three to eight slots per pole per phase, so that the winding is not uniformly distributed and the magnetizing effect changes more or less abruptly, as shown in Fig. 14. Moreover, the contour of the broken line in the figure changes somewhat with changes in the current, and the maximum value varies up and down through a limited range, which becomes less as the number of slots per pole is increased. Notwithstanding these changes, it has been

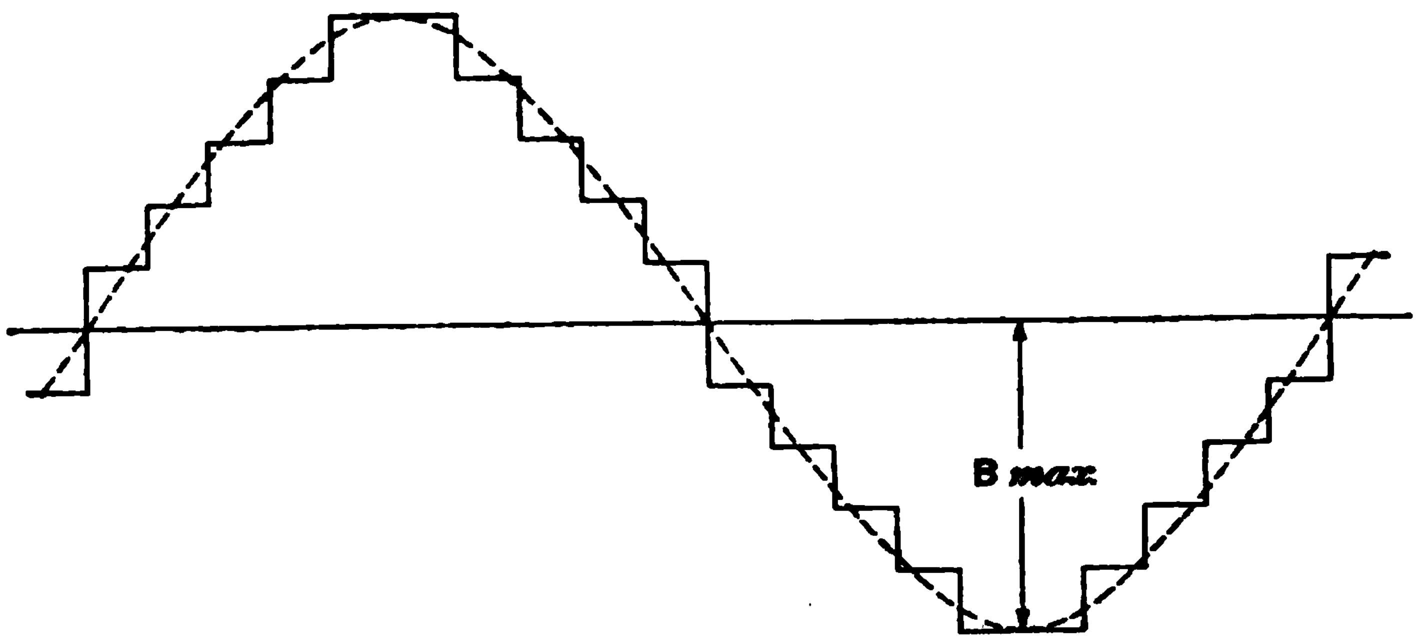


FIG. 14

found that the actual flux in induction motors approximates a sine wave quite closely, and it is generally assumed to have such form when making calculations.

MAGNETIZING CURRENT

56. The **magnetizing current** of an induction motor is rather difficult to calculate accurately, because the air gap is very short and slight variations in its length, which are almost unavoidable with ordinary shop methods, may lead to quite a discrepancy between the observed current and the calculated current. Nearly all the magnetizing ampere-turns on the stator are needed to force the flux across the air gap, the number required for the iron part being comparatively small, because of the low densities used in the iron. With a motor having an air gap of, say, .03 inch, a variation of only 3 mils, or $\frac{3}{1000}$ inch, would make a difference of about 10 per cent. in the magnetizing current.

57. The following formula gives very fair results for calculating the magnetizing component OB, Fig. 11, of the no-load current, and makes some allowance for the iron part of the magnetic circuit. The no-load current OA is found by combining the part AB representing the no-load losses with the magnetizing current; since AB is at right angles to OB and angle AOB is small, OA is very nearly equal to OB. If I_e is the magnetizing current in amperes per phase, then

$$I_e = \frac{p\,\Phi\,l'_g}{1.7\,m\,T_p\,T\,l},$$

in which p = number of poles;
Φ = flux per pole;
l'_g = effective length of air gap, in inches, corrected for fringing;
m = number of phases;
T_p = turns in series per phase;
T = pole pitch, in inches;
l = length of iron parallel with shaft, in inches.

If both the stator and the rotor slots are closed, or nearly so, l'_g may be taken equal to the actual length of air gap, no correction for fringing being necessary; but if the stator slots are open and the rotor slots closed, it is on the safe side to take l'_g equal to the actual air gap multiplied by the ratio $\frac{\text{slot pitch}}{\text{width of tooth}}$. As the magnetizing current is dependent directly on the length of the effective air gap, the desirability of using the shortest possible air gap is evident.

Example.—The inside diameter of the stator of an eight-pole three-phase induction motor is 22 inches, and the length of the core parallel with the shaft is 6 inches. The flux per pole is 1,000,000 lines, and the actual length of the single air gap between stator and rotor is .03 inch. Both stator and rotor have closed slots, there being 96 stator slots with 6 conductors per slot. Calculate the magnetizing current per phase.

Solution.—

$$\text{Pole pitch } T = \frac{\pi d}{p} = \frac{3.1416 \times 22}{8} = 8.64 \text{ in.}$$

Both stator and rotor slots are closed, so that the effective air gap l'_g may be taken equal to the actual gap, or .03 in. There are 96 slots,

or 32 per phase. This gives $32 \times 6 = 192$ conductors per phase, and $T_p = 192 \div 2 = 96$, $l = 6$, $\Phi = 1{,}000{,}000$. Substituting in the formula,

$$I_e = \frac{8 \times 1{,}000{,}000 \times .03}{1.7 \times 3 \times 96 \times 8.64 \times 6} = 9.5 \text{ amperes, nearly. Ans.}$$

MAGNETIC DENSITIES

58. Stator.—The density in the stator teeth should not be forced very high, particularly in 60-cycle motors. High tooth densities lead to excessive core loss and tend to increase the magnetizing current. It was shown in connection with the circle diagram that large magnetizing current tends to make the power factor low; hence, every effort should be made to obtain low magnetizing current, provided it does not make the design poor in other respects. In 60-cycle motors, the maximum tooth density is usually from 50,000 to 60,000 lines per square inch, but in 25-cycle motors it may be higher, 70,000 to 80,000 being common values. At any given instant, there are only a few teeth at the center of each pole in which the density is a maximum.

In the stator core back of the slots the density should be comparatively low, because the volume of iron is considerable and the loss per cubic inch must be kept down. In 60-cycle motors, the maximum core density should be from 40,000 to 50,000 lines per square inch; in 25-cycle machines, it may be as high as 60,000 lines without causing undue core loss. If Φ is the total stator flux per pole, the maximum value of the flux through the core section under the slots is $\frac{1}{2}\Phi$, which, divided by the allowable density, gives the net cross-section of iron. It is advisable in designing induction motors to allow a liberal amount of iron in the stator core, for it is sometimes desirable to wind the motor for a smaller number of poles than originally intended, and the extra iron will be available for carrying the larger flux per pole.

59. Rotor.—The magnetic densities in the rotor can be considerably higher than those in the stator without appreciably increasing the core loss. The frequency of the

magnetic reversals in the rotor core is so low that high densities are not objectionable, except as they help increase the magnetizing current. In a 60-cycle motor with a full-load slip of 5 per cent., the frequency of the magnetic reversals in the rotor is only 3 cycles per second, so that the loss per cubic inch even at high density becomes very small. In both 60- and 25-cycle motors, the density at the narrowest part of the rotor teeth is frequently from 100,000 to 110,000 lines per square inch.

The rotor core might be worked at a high density, but usually a depth under the slots about equal to that in the primary is required for mechanical strength, and it is customary to make the density in this part about the same as in the stator.

60. Air Gap.—Since most of the magnetomotive force of the stator windings is required to force the flux across the air gap, the density must be kept comparatively low, otherwise a large magnetizing current will result. The maximum density in the air gap should not exceed 30,000 lines per square inch, and it is frequently less than this.

TABLE III

LENGTH OF AIR GAP FOR INDUCTION MOTORS

Rotor Diameter Inches	Air Gap Mils
5 to 8	10 to 15
9 to 12	20 to 25
15 to 25	30 to 40
30 to 50	50 to 60
60 to 100	70 to 150

LENGTH OF AIR GAP

61. The air gap is made as short as mechanical considerations will permit. There is therefore considerable difference in the air gaps used by different builders. It is now common practice to provide adjustment for wear in the bearings of large motors, so that the rotor can be kept centered. Where such provision is made, the clearance can be safely made somewhat smaller than where no adjustment is possible.

The cores of small rotors can be very accurately mounted and centered; but in large machines where the diameter is such

that the core must be built up of segmental punchings, there is bound to be some slight variation, and a larger air gap must be allowed. The usual lengths of the air gap are shown in Table III, but these are by no means the only ones in use.

SHAPE AND NUMBER OF SLOTS

62. Shape of Slots.—There has been much discussion in regard to the best form of slots for induction motors, that is, whether they should be open, entirely closed, or partially closed. Entirely closed slots are used comparatively little, as the bridge of iron over the top of the slot, even though it is made quite thin, forms a good path for leakage lines around the conductors bedded in the slot, and thus tends to increase the reactance of the windings and to lower the power factor. In partially closed slots, there is a small opening between the overhanging tips of the teeth, and this opening introduces considerable reluctance in the path of the leakage lines.

It is now generally conceded that motors can be built with either open or partially closed slots and have equally good characteristics, but with open slots the motor must be made somewhat larger. On the other hand, with open slots, the coils can be wound on forms and be completely insulated before being placed in position, whereas, with partially closed slots the coils must be wound directly on the core. The saving in material with partially closed slots may therefore be offset by the increased cost of labor, and in many cases it is a rather difficult question to decide which construction will give the best all-around results.

On the rotor, the general custom is to use practically closed slots, especially if the winding is of the squirrel-cage type. Even in the case of Y-wound rotors, arranged for the insertion of resistance at starting, the winding can usually be designed for comparatively few conductors per slot. These conductors, which are usually in the form of copper bars, can be easily pushed into the slots from one end and afterwards bent to the required shape to form the end connections.

In case the size of the motor or the supply voltage is such that the stator winding requires only a few conductors per slot, the winding can frequently be made of copper bars or strips, and the closed slots are not then so objectionable from the labor point of view as when each coil contains a comparatively large number of turns.

The principal advantage of closed slots is that they reduce the reluctance of the air gap by providing a greater cross-sectional area for the flux, and the bunching of the lines of force, which is always present with open slots, is avoided. Thus, for a given polar area and a given magnetizing force, a motor with closed slots and a lower gap reluctance will have a larger flux per pole than one with open slots, and also a correspondingly greater output.

63. Number of Slots.—Although a large number of slots per pole is desirable, there is a practical limit to the number that can be used. Motors are seldom made with less than three slots per pole per phase. For 60-cycle motors of moderate size, four slots per pole per phase is very commonly used. This makes twelve slots per pole for three-phase motors, and the same punchings can be used for two-phase motors, giving six slots per pole per phase. Since the larger three-phase motors usually have a greater pole pitch and more room for slots, six slots per pole per phase, or eighteen slots per pole, is used. In 25-cycle motors, the number of poles is usually much smaller than in 60-cycle motors, and a correspondingly larger number of slots per pole can be used, comparatively small three-phase 25-cycle motors (from 20 to 100 horsepower) frequently having eighteen slots per pole. In selecting the number of slots for a three-phase motor, it is advisable to make the number such that the same punchings can be used for a two-phase machine if desired; that is, have the number of slots per pole divisible by both 2 and 3, for example, 12, 18, 24, etc.

CURRENT DENSITY IN STATOR AND ROTOR CONDUCTORS

64. Ventilation.—In modern induction motors, a great deal of attention has been paid to ventilation. The yoke that supports the stator punchings is made as open as possible, in some cases being a mere skeleton frame. Fan blades are frequently attached to the rotor, and air ducts are provided in both stator and rotor cores. Induction motors have much smaller air gaps than alternators, and do not have spaces between poles to give the air easy access to the face of the stator; hence, it is more difficult to secure good ventilation in induction motors than in alternators.

65. Circular Mils per Ampere.—The number of circular mils per ampere in the stator conductors is usually 400 in induction motors having very good ventilation to 900 in poorly ventilated motors. When existing punchings are used for motors of different voltages, the greater space required for insulating high-voltage windings necessitates, because of lack of space, a smaller allowance of circular mils per ampere than in low-voltage windings. In the rotor, the circular mils per ampere are usually as large as in the stator, and in many cases considerably larger, since there are comparatively few heavy conductors, and very little space is occupied by insulation. The bars in squirrel-cage rotors are generally made of hard-drawn copper, because this material is more easily drilled and tapped for bolting to the end rings than soft copper.

66. Ampere-Conductors per Inch.—In modern induction motors, the number of ampere-conductors per inch of stator periphery is usually from 300 to 700, the lower value being for small motors, or those in which the ventilation is not very effective. Well-ventilated motors having an output over 10 horsepower, on comparatively low pressures, can carry safely from 400 to 500 ampere-conductors per inch. If the watts $I^2 R$ loss per square inch of stator face, as given by the ratio

$$\frac{\text{ampere-conductors per inch}}{\text{circular mils per ampere}},$$

is over 1, there is danger of the motor overheating unless special precautions are taken to secure exceptionally good ventilation. In working out a design, the value of this ratio should be noted after the ampere-conductors per inch and the circular mils per ampere have been decided on. If it is too high, either the cross-section of the conductor should be increased or the number of ampere-conductors per inch reduced.

SLIP

67. The drop in speed from no load to full load, or the slip, must be such as to cause the generation of sufficient electromotive force in the rotor to set up a rotor current large enough to give the requisite torque. For a given electromotive force in the rotor, the current depends on the resistance of the rotor winding; and, as before stated, the percentage slip is practically equal to the percentage $I^2 R$ loss in the secondary. When a rotor has a winding arranged for the insertion of external resistance, the resistance of the winding is made as low as possible, and the slip is therefore comparatively small. Generally speaking, squirrel-cage windings, with which external resistance cannot be used, must have enough resistance to give a full-load slip of 3 to 5 per cent., in order to secure sufficient starting torque without taking excessive current from the line. The resistance of the rotor bars is small, since they are of copper and have considerable cross-section. It is the general practice of manufacturers to provide extra resistance in the end rings, from which the heat is readily dissipated. Knowing the required slip, the total $I^2 R$ loss in the rotor is known; and from the full-load secondary current and the known dimensions of the rotor bars, the loss in the bars can be calculated. This value subtracted from the total $I^2 R$ loss gives the loss that should be allowed in the two end rings, which should be proportioned accordingly.

68. Loss in End Rings.—In Fig. 15 (*a*), which is a development of a rotor winding, *a*, *a* represent rotor bars attached to the end rings *r*, *r'*. The vertical dot-and-dash lines represent the centers of three consecutive poles *N*, *S*, *N* at a given instant. The current in the bars directly under the poles is a maximum, as indicated by the length of the

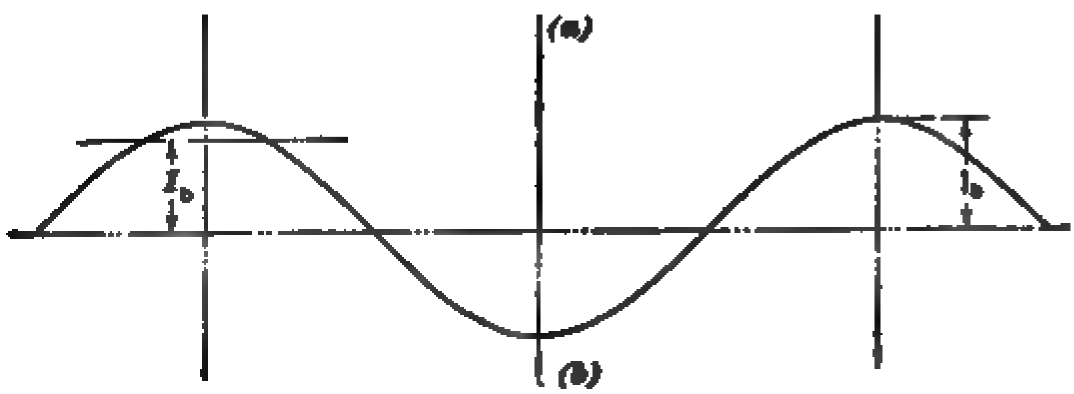


FIG. 15

arrows, and gradually decreases according to the sine law on each side of the pole center.

If $\mathbf{I}_b$ is the maximum current in the bars and I_b the effective current, then, $\mathbf{I}_b = I_b\sqrt{2}$, and the average current in the bars is

$$\frac{2}{\pi}\,\mathbf{I}_b = \frac{2}{\pi}\,I_b\sqrt{2}$$

The current in the end rings is the sum of the currents of the bars, and is a maximum at a section *b c* midway between two adjacent poles. This maximum is the sum of the currents flowing through one-half the bars under each pole. Therefore, if N_b is the number of bars per pole, the maximum current in the end rings is

$$\frac{N_p}{2} \times \frac{2}{\pi} I_b \sqrt{2}$$

and the effective current in the end rings is

$$\frac{\text{maximum current}}{\sqrt{2}} = \frac{N_p}{2} \times \frac{2}{\pi} I_b = \frac{N_p}{\pi} I_b$$

If R is the resistance of the portion of the end ring between two adjacent bars, N the total number of bars, and $\frac{1}{\pi^2} = .1$, then, the $I^2 R$ loss in each ring is

$$\left(\frac{N_p}{\pi} I_b\right)^2 R N = .1\, N_p^2 I_b^2 R N \qquad (1)$$

or, $I^2 R$ loss in both rings is

$$.2\, N_p^2 I_b^2 R N \qquad (2)$$

and
$$R = \frac{I^2 R \text{ loss in both rings}}{.2\, N_p^2 I_b^2 N} \qquad (3)$$

From formula **3**, the resistance R of the ring between bars can be calculated; also, if the specific resistance of the end-ring material and the length of current path from bar to bar are known, the required cross-section of the ring can be obtained. End rings are generally made of composition metal, the specific resistance of which varies through a wide range, depending on the materials of which the metal is made.

Although the resistance that the ring should have can be calculated, it is by no means easy to construct rings of the required resistance or to build a motor having exactly the slip estimated. The resistance of the bolted contacts between rings and bars has an appreciable influence, and this resistance cannot be readily calculated. Again, the specific resistance of cast rings is more or less variable, and the effective length of the ring between bars is somewhat difficult to estimate. Formula **3**, however, is useful as a guide in determining the cross-section, and even if the slip does vary 1 or 2 per cent. from that estimated, it is usually not of much consequence where motors are used for general power purposes.

POWER FACTOR AND EFFICIENCY

69. It is desirable that both the power factor and the efficiency of a motor should be as high as practicable. High power factor alone does not necessarily indicate a good design, since it may be obtained at the expense of efficiency. The important point is to have the product of power factor and efficiency (apparent efficiency) as high as possible, because on this product depends the current input for a given power output. Motors for low frequency (25 cycles) have a lower reactance than those of high frequency (60 cycles); hence, 25-cycle motors generally have the higher power factor.

In explanation of the lower reactance, it may be stated that low-frequency motors have fewer poles than those of high frequency, thus giving longer pole pitch and lower leakage factor. The low-frequency motor, however, usually has the lower efficiency, because the flux density in the iron is necessarily higher and the speed is usually lower, thus requiring more material than a high-frequency motor for the same output. Both the increased weight of material and the increased flux density in the low-frequency motor cause increased losses.

TABLE IV

EFFICIENCIES FOR SQUIRREL-CAGE INDUCTION MOTORS

Horsepower Output	Efficiencies		Power Factors	
	60 Cycles	25 Cycles	60 Cycles	25 Cycles
5	.830	.790	.850	.890
7½	.840	.795	.860	.895
10	.845	.800	.870	.900
20	.870	.840	.880	.910
30	.890	.875	.885	.920
50	.895	.880	.890	.925
100	.900	.890	.900	.930

The values of power factor and efficiency vary considerably according to the design, but Table IV shows approximate values for belted motors of the squirrel-cage type. These values are for motors running at ordinary standard speeds.

SPEED

70. Induction motors are made to run at a great variety of speeds, and it is not possible to lay down any definite speed as pertaining particularly to a motor of given output. For belted motors, manufacturers usually adopt as high speed as practicable, without exceeding a maximum belt speed of 5,000 feet per minute. High rotative speed permits the use

TABLE V

POSSIBLE SPEEDS OF INDUCTION MOTORS

60 Cycles		25 Cycles	
Number of Poles	Speed	Number of Poles	Speed
2	3,600	2	1,500
4	1,800	4	750
6	1,200	6	500
8	900	8	375
10	720	10	300
12	600	12	250
14	514	14	214
16	450	16	187

of a small motor frame for a given output, and hence lowers the cost. Again, high speed requires a small number of poles, thus giving comparatively large pole pitch and tending to secure a low leakage factor. In many cases, however, high rotative speed is undesirable for mechanical reasons. The speed of the motor is frequently determined by the required speed of the machine to be driven. If the motor is to be direct-connected to the driven machine, the speed is

thereby fixed, and work of this kind gives rise to a great number of special speeds.

The number of useful speeds obtainable with 60-cycle motors is much greater than with 25-cycle motors, as can be seen from the comparison in Table V.

The useful speeds of belted motors lie between approximate limits of 500 and 1,800 revolutions per minute. Within these limits, 25-cycle motors can be built for only three speeds, while 60-cycle motors can be built for six. With six poles, a 25-cycle motor gives a speed of 500, and with a larger number of poles the speeds become so low that they are suitable only for direct-connected motors or belted ones of large output.

DESIGN OF ALTERNATING-CURRENT APPARATUS

(PART 4)

INDUCTION MOTORS

MECHANICAL CONSTRUCTION

CONSTRUCTION OF STATOR

1. The **mechanical construction** of induction motors in many respects follows very closely that of revolving-field alternators. Some features, however, peculiar to induction motors, require special explanation.

The stator core and windings are constructed in almost exactly the same manner as the stator of an alternator. The punchings are supported in a yoke that may take any of the forms previously described for alternators, but the usual plan is to select one adapted to the support of end shields in which the bearings can be placed. This method of supporting the bearings, as a rule, is cheaper than placing them in pedestals for which a base, or bedplate, must be provided. Moreover, the end shields stiffen the yoke so that it can be made considerably shallower and lighter than would be necessary if no end shields were used. When the motor is of such size that two bearings are sufficient, the stator is provided with feet that rest directly on the slide rails, and no bedplate is required. When the motor is so large that

an outboard bearing is necessary, the stator feet are bolted to a bedplate, which also carries the outboard bearing. Bearings mounted in end shields bolted to the yoke secure accurate centering of the rotor; this is a feature of special importance in induction motors, since the clearance between stator and rotor is so small that a slight displacement makes the unbalanced magnetic pull excessive.

2. Stator Punchings.—The stator core should be so carefully built up and the punchings so made that very little, if any, filing is required in the slots to make them smooth enough to take the coils. The precautions taken in alternators to prevent eddy-current loss are also necessary in induction motors.

In small motors having rotor diameters of about 30 inches, or less, the stator punchings are in one piece and hence are self-supporting. Such punchings are placed in the yoke and clamped between end plates, a small key being provided to make the disks line up properly. The stators of motors of larger diameter are usually made of segmental punchings supported by bolts or dovetails in the same way as in alternators.

CONSTRUCTION OF ROTOR

3. Rotors With Polyphase Windings.—The rotating part presents a number of features not found in alternators; and the construction varies considerably, depending on whether the rotor is of the squirrel-cage type or is provided with a definite polyphase winding for the insertion of resistance. Polyphase rotor windings are nearly always made for three phases, since this style of winding requires only three collector rings and works all right even if the stator is wound two-phase and connected to a two-phase circuit. Such a rotor winding is arranged in the same way as that for a three-phase stator, and is generally of the two-layer type. The three terminals are connected to the collector rings, and if the latter are mounted outside the bearing, it is necessary to bring the leads through a hole bored into the shaft.

When the external resistance is used only at starting and not for speed-regulating processes, a short-circuiting device is frequently provided for connecting the three rings together, so that the brushes carry current only during the starting interval. In some cases, provision is also made for lifting the brushes off the rings, but this is hardly necessary, because when carbon brushes are used, the wear is very slight.

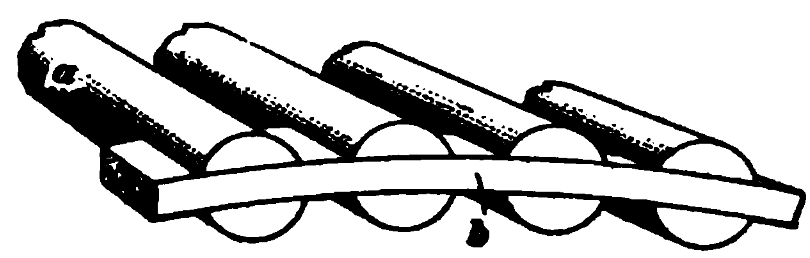


FIG. 1

4. Squirrel-Cage Rotors.—In all except very small motors, it is customary to make the bars, or conductors, for **squirrel-cage rotors** of rectangular cross-section. This form of bar is easily bolted to the end rings and permits the use of rather wide, shallow slots. The bars are usually fastened to the end rings by means of bolts or capscrews, but in some small motors where round bars are

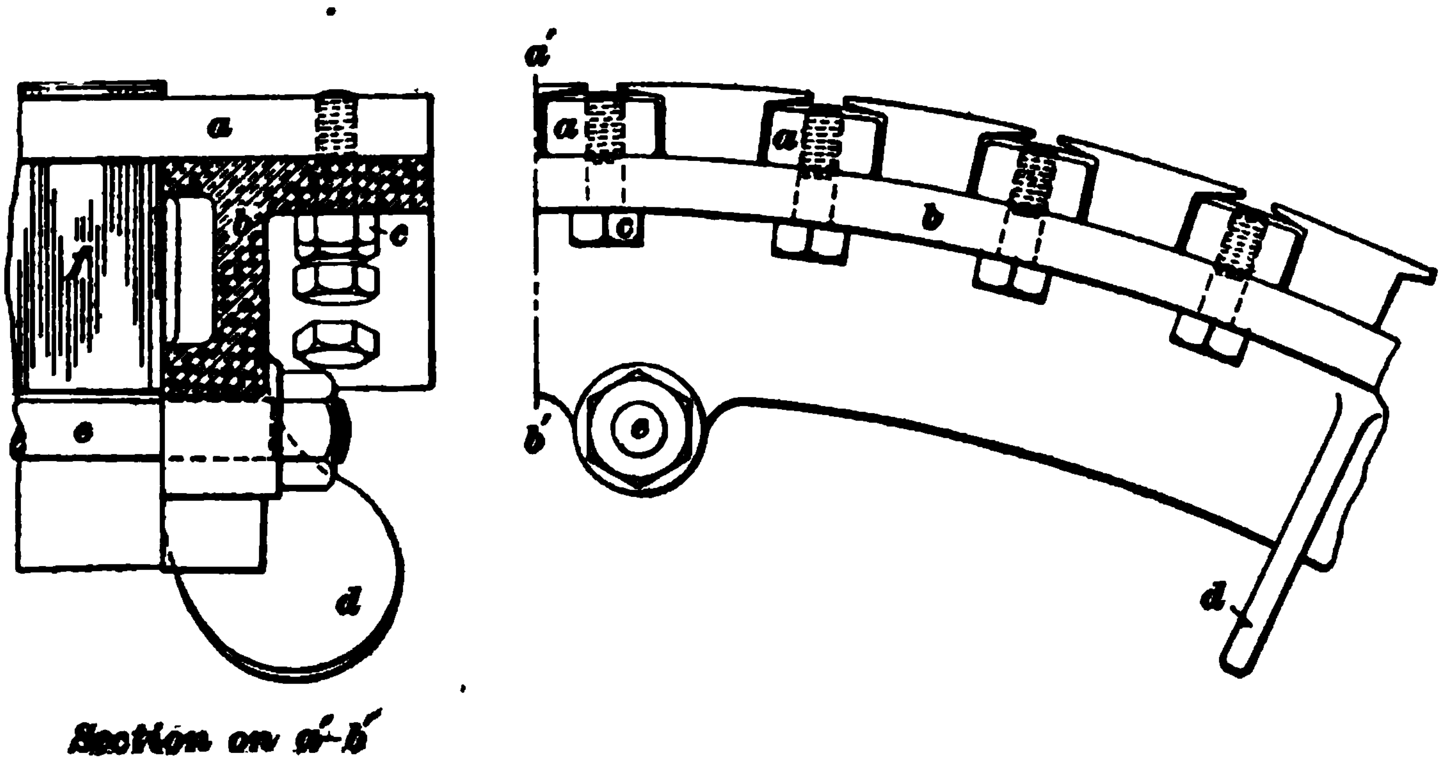


FIG. 2

used, the ends of bars *a*, Fig. 1, are slotted to receive the ring *b*, which is soldered in place.

Another construction for small motors is to make the end heads, between which the laminations are clamped, of brass castings, into which holes are drilled corresponding with the bars. The ends of the bars projecting through the holes are

riveted and soldered to the end plates, which thus answer the same purpose as end rings.

Motors of any considerable size, say over 5 horsepower, usually have regular end rings to which the bars are bolted. Sometimes, these are made to serve the purpose of rotor end

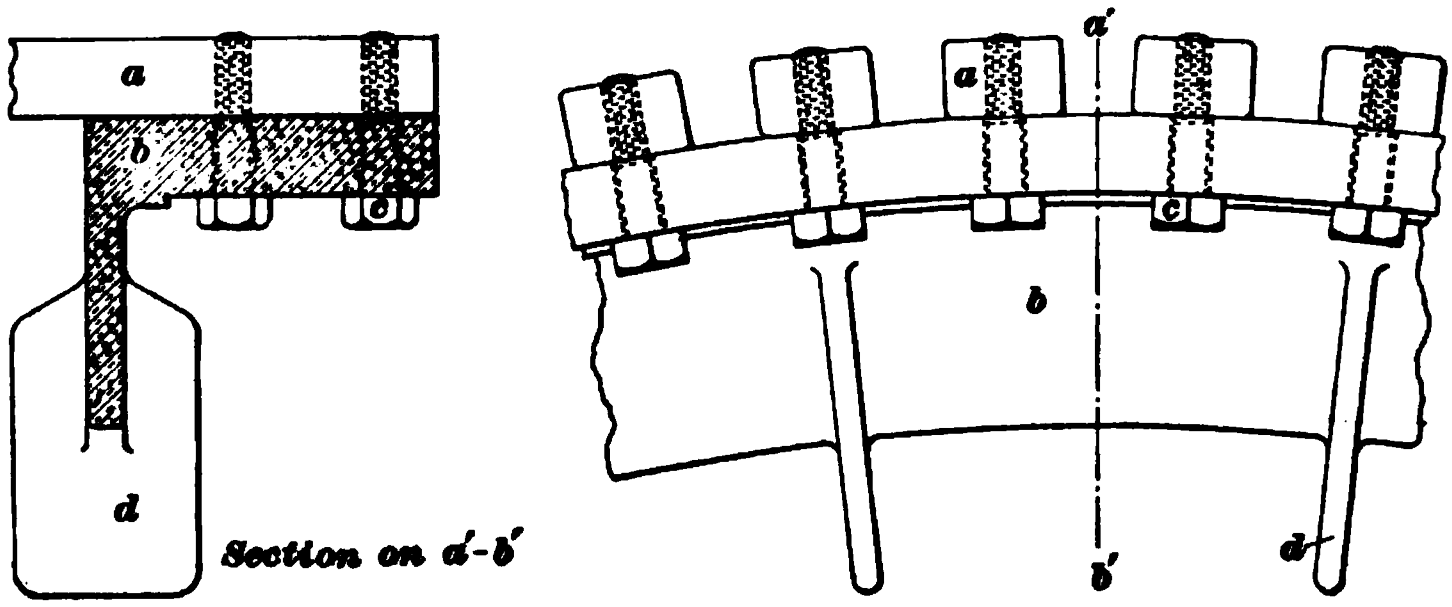


FIG. 3

heads, as shown in Fig. 2, where *a*, *a* are the rotor bars bolted to the cast ring *b* by means of capscrews *c*. The rings are shaped so as to have considerable stiffness and are clamped against the laminations by bolts *e* that pass under the core. As previously explained, it is necessary to dissipate considerable energy in the end rings in order to secure a reasonably

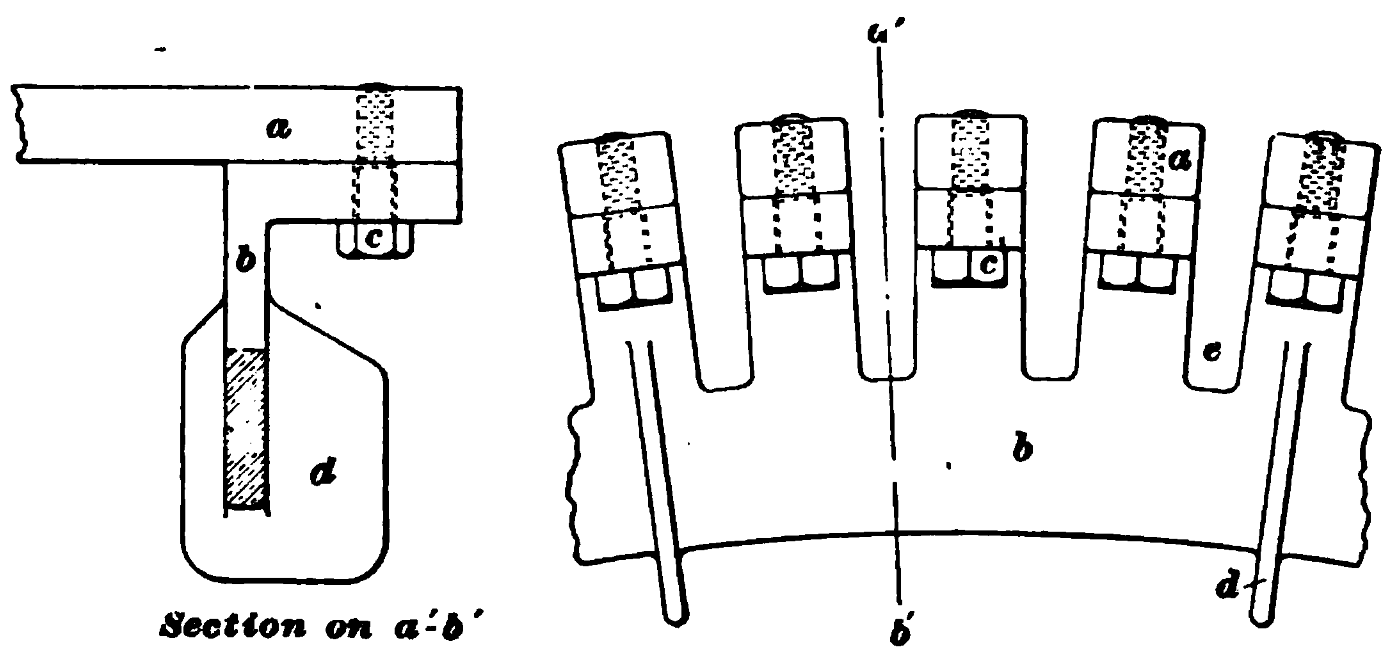


FIG. 4

good starting torque. If, therefore, thorough ventilation is not provided, the rings may become too hot; for this reason, the method of mounting should always be such that air can circulate freely around them. Some makers cast fan blades *d* on the rings, and these blades, by stirring the air, assist not

only in dissipating heat from the rings themselves, but also aid materially in keeping the end connections of windings cool.

Fig. 3 shows an end ring that is supported either wholly by bars, or by bars together with projections on the rotor spider, the letters indicating the various parts being the same as in Fig. 2.

Fig. 4 shows a form of ring sometimes used when con-

Fig. 5

siderable resistance must be obtained between bars. The metal is cut down between the bars, as at *e*, so that the effective cross-section of the ring is reduced.

Fig. 5 is an end view of a squirrel-cage motor, showing one of the end rings. In this case the rings are not provided with fan blades, and are held in place by the rotor bars and by projections on the spokes of the spider.

CONNECTIONS

5. The terminals of the stator winding are connected directly to the motor terminal board. A squirrel-cage rotor has no connections whatever with any outside circuit; a rotor wound for use with external resistance is provided with collector rings, on which brushes that collect the current slide. The circuit through the rotor windings, collector rings, brushes, and resistance is entirely separate from the supply circuit and the stator windings.

The terminals of high-voltage motors should be covered in some way. Fig. 6 shows a terminal much used for this

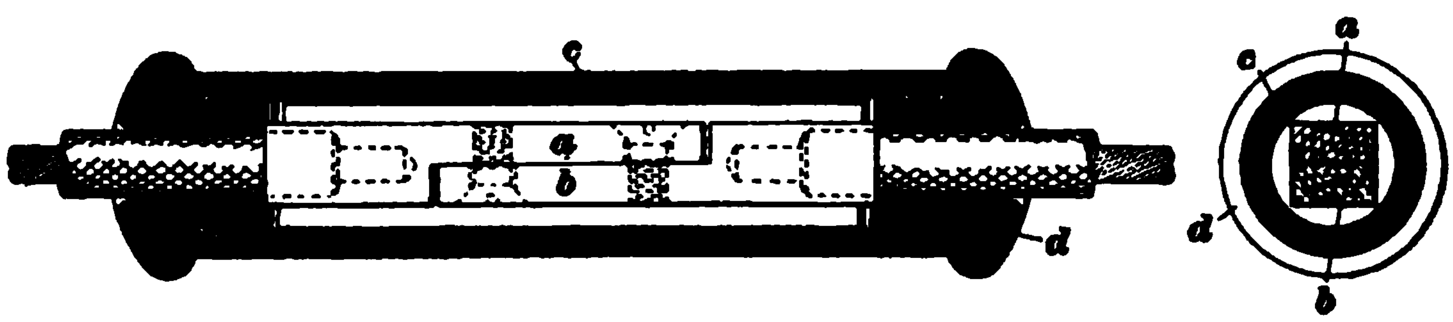


FIG. 6

purpose. The leads from the motor winding and the line, respectively, are soldered into brass terminals *a*, *b*. The terminals are fastened together by countersunk screws, and the whole is covered by an insulating tube *c* provided with end bushing *d* of ebonite or molded insulating material. The slight projections formed by the terminals *a*, *b* prevent the protecting tube with its bushing from sliding along the cable. This terminal affords protection against accidental shocks or short circuits, and also allows the motor to be readily disconnected from the line.

OUTPUT OF INDUCTION MOTORS

6. Before taking up an example of induction-motor design it will be of assistance to obtain the relation between the output and the various elements entering into the electrical design. A formula very similar to those already explained for direct- and alternating-current generators is found to hold for induction motors.

Let H. P. = motor output, in horsepower;
K. V. A. = motor input, in kilovolt amperes, that is, apparent K. V. A. × 1,000 = apparent watts input;
e = full-load efficiency;
p. f. = full-load power factor.

Then, $$\text{K. V. A.} \times 1{,}000 = \frac{\text{H. P.} \times 746}{e \times \text{p. f.}}$$

or, $$\text{apparent watts input} = \frac{\text{H. P.} \times 746}{e \times \text{p. f.}} \qquad (1)$$

The product of power factor and efficiency of moderate-sized induction motors are not far from .746; hence, it is quite common when making preliminary calculations to take the apparent kilowatts input, or kilovolt amperes, as numerically equal to the output in horsepower. Thus, at full load, the input of a 10-horsepower motor would be 10-kilovolt amperes, or 10 apparent kilowatts. It is assumed, then, that for any given motor the apparent watts input is known.

If E_p is the voltage induced per phase, T_p the number of turns in series per phase, Φ the flux per pole, n the frequency, and k a coefficient having a value of 4.2 for three-phase and 4 for two-phase winding (see *Design of Alternating-Current Apparatus*, Part 3), then,

$$E_p = \frac{k\,\Phi\,T_p\,n}{10^8} \qquad (2)$$

Or, if C_p is the number of *conductors* per phase, $T_p = \frac{1}{2}\,C_p$, and

$$E_p = \frac{k\,\Phi\,C_p\,n}{2 \times 10^8} \qquad (3)$$

If I_p is the current supplied to each phase, m the total number of phases, and W the total apparent watts, then,

$$W = m\,E_p\,I_p$$
$$= \frac{m\,I_p\,k\,\Phi\,C_p\,n}{2 \times 10^8}$$

$m\,I_p\,C_p$ is the total ampere-conductors on stator; calling this A_c,

$$W = \frac{k\,\Phi\,A_c\,n}{2 \times 10^8} \qquad (4)$$

If p is the number of poles, and S the speed in revolutions per minute, then,

$$n = \frac{pS}{120}$$

Also, if d is the diameter of the stator face and l the spread of the laminations measured parallel with the shaft, then,

$$\text{area of one pole face} = \frac{\pi d l}{p}$$

If $\mathbf{B}_g$ = maximum density in the air gap and there is a sine distribution of magnetism, the average density is

$$\mathbf{B}_{av} = \mathbf{B}_g \times \frac{2}{\pi}$$

$$\begin{aligned} \Phi &= \mathbf{B}_{av} \times \text{pole face area} \\ &= \mathbf{B}_g \times \frac{2}{\pi} \times \frac{\pi d l}{p} = \frac{2\,\mathbf{B}_g d l}{p} \end{aligned} \qquad (5)$$

Placing the values of Φ and n in formula **4**,

$$W = \frac{k \times \dfrac{2\,\mathbf{B}_g d l}{p} \times A_c \times \dfrac{PS}{120}}{2 \times 10^8}$$

or,

$$W = \frac{k\,\mathbf{B}_g d l A_c S}{120 \times 10^8}$$

If K is the ampere-conductors per inch of stator periphery, then,

$$K = \frac{A_c}{\pi d}; \text{ or, } A_c = K \pi d$$

and

$$W = \frac{k\,\mathbf{B}_g d^2 l K S \pi}{120 \times 10^8},$$

from which

$$d^2 l = \frac{120 \times 10^8 \times W}{\pi k\,\mathbf{B}_g K S} \qquad (6)$$

For three-phase motors, k = 4.2, and

$$d^2 l = \frac{120 \times 10^8 \times W}{\pi \times 4.2 \times \mathbf{B}_g K S} = \frac{9.1\, W\, 10^8}{\mathbf{B}_g K S} \qquad (7)$$

For two-phase motors, k = 4, and

$$d^2 l = \frac{120 \times 10^8 \times W}{\pi \times 4 \times \mathbf{B}_g K S} = \frac{9.5\, W \times 10^8}{\mathbf{B}_g K S} \qquad (8)$$

The number of cylindrical inches $d^2 l$ is therefore directly proportional to the input, and inversely proportional to the

air-gap density, ampere-conductors per inch of periphery, and speed. The air-gap density and ampere-conductors per inch are fixed within certain limits. The speed is usually fixed by the nature of the work that the motor has to do, so that, in any given case, the value of $d^2 l$ can be obtained approximately and used in determining the final dimensions.

DESIGN OF A 50-HORSEPOWER INDUCTION MOTOR

DIMENSIONS OF STATOR

7. Specifications.—To illustrate the design of an induction motor the following specifications will be assumed: Output at pulley, 50 horsepower; frequency, 60 cycles per second; speed, 720 revolutions per minute; voltage at terminals, 550; number of phases, 3. At full load, the motor should have an efficiency of not less than .89 and a power factor of .89, the product of efficiency and power factor being .792.

8. Number of Poles.—Since the speed is to be 720 revolutions per minute and the frequency 60 cycles, the number of poles

$$p = \frac{120\,n}{S} = \frac{120 \times 60}{720} = 10$$

9. Full-Load Current.—The approximate full-load current can be calculated by using the specified values of the power factor and efficiency as follows:

$$\text{Full-load current input per line} = \frac{\text{H. P.} \times 746}{\sqrt{3} \times E \times \text{p. f.} \times e}$$

Hence, for the motor to be designed,

$$\text{current per line} = \frac{50 \times 746}{\sqrt{3} \times 550 \times .89 \times .89}$$
$$= 49.5 \text{ amperes, nearly}$$

10. General Dimensions.—The maximum air-gap density may be assumed at 30,000 lines per square inch, and the ampere-conductors per inch at 450. Both of these values

are conservative, especially the latter. The apparent watts input, as determined by formula **1**, Art. **6**, is

$$W = \frac{50 \times 746}{.89 \times .89} = 47{,}100$$

The speed S is 720 revolutions per minute, and the motor is to be three-phase; hence, the cylindrical inches of the armature, as determined by formula **7**, Art. **6**, are

$$d^2 l = \frac{9.1 \times 47{,}100 \times 10^8}{30{,}000 \times 450 \times 720} = 4{,}400, \text{ approximately}$$

Either of the dimensions d or l being determined, the other is then easily found. The diameter should be determined first. To secure a good power factor, it is desirable to use a large diameter, but this makes the peripheral speed high, and the core becomes very narrow as measured parallel with the shaft. The larger the diameter, the larger also must be the yoke that supports the stator core, and the greater the diameter and weight of the bearing housings. In general, for motors of ordinary type, the diameter should be such that the length of core will be from seven-tenths to two times the pole pitch.

It is customary to build motors of different outputs by using the same punchings and making the core longer or shorter, as may be required. In such cases, since the pole pitch remains fixed, the ratio of length of core to pole pitch undergoes considerable variation. For the present case a diameter of 24 inches will be taken. This gives a peripheral speed of about 4,500 feet per minute, which is not at all high for a motor of this size. If the motor had fewer poles, say six or eight, a somewhat smaller diameter might be used; but with ten poles, the diameter cannot be made less without danger of giving a large amount of leakage and correspondingly poor power factor. Since $d^2 l = 4{,}400$, and d is taken as 24 inches, then,

$$l = \frac{4{,}400}{d^2} = \frac{4{,}400}{24^2} = 7.64, \text{ say } 7\tfrac{5}{8}, \text{ inches}$$

The pole pitch is

$$\frac{24 \times \pi}{p} = \frac{24 \times 3.1416}{10} = 7.54 \text{ inches}$$

Therefore, the pole pitch is about equal to the length of the core, thus making the opening in the coil approximately square. This should give a satisfactory winding.

11. Number of Slots.—Motors of this size generally have either twelve or eighteen slots per pole, so that they can be wound either two- or three-phase. If the number of slots is made too great, the teeth become so narrow that their flux density is excessively high. In the motor to be designed, the diameter, 24 inches, is not large enough to allow the use of eighteen slots per pole, so twelve will be used, making the total number in the stator 120.

12. Flux per Pole.—The maximum air-gap density is not to exceed 30,000 lines per square inch. From formula **5**, Art. **6**,

$$\text{flux per pole } \Phi = \frac{2\,\mathbf{B}_g\,d\,l}{p}$$

In this case, $d = 24$ inches and $l = 7.75$ inches; hence,

$$\Phi = \frac{2 \times 30{,}000 \times 24 \times 7.75}{10} = 1{,}116{,}000 \text{ lines}$$

13. Conductors per Slot.—The number of conductors per slot will depend to some extent on the method of connecting the phases. Since the Y method will require the smaller number, it will be tried first. If the number of conductors does not fit well in the slot, the Δ arrangement can be tried. With a Y winding, the line voltage equals the volts per phase times $\sqrt{3} = E_p\sqrt{3}$, or $E_p = \frac{550}{\sqrt{3}}$. From formula **2**, Art. **6**,

$$E_p = \frac{k\,\Phi\,T_p\,n}{10^8}$$

In this case, $k = 4.2$ for a three-phase motor, $\Phi = 1{,}116{,}000$, and $n = 60$; hence,

$$\frac{550}{\sqrt{3}} = \frac{4.2 \times 1{,}116{,}000 \times T_p \times 60}{10^8}$$

$$T_p = \frac{550 \times 10^8}{4.2 \times 1{,}116{,}000 \times 60 \times \sqrt{3}} = 113, \text{ approximately}$$

That is, with the given flux and speed, the number of turns should be 113 and the number of conductors 226. There are forty slots per phase, and six conductors per slot will give 240 conductors per phase, the nearest practicable number to 226. The use of 240 conductors, or 120 turns, instead of 226 will necessitate the use of a somewhat smaller flux, determined as follows:

$$\Phi = \frac{550 \times 10^8}{4.2 \times 120 \times 60 \times \sqrt{3}} = 1{,}050{,}000 \text{ lines}$$

14. Stator Conductor.—The full-load current is 49.5 amperes per line, and with a Y winding, the current in each phase will be the same as the current per line. Allowing 600 circular mils per ampere, the cross-section will be $49.5 \times 600 = 29{,}700$ circular mils. No. 6 B. & S. round wire has a cross-section of 26,250 circular mils, or about 530 circular mils per ampere; this might do, but a wire of square cross-section having its side the same as the diameter of No. 6 B. & S. wire, and known as No. 6 square wire, would necessitate no larger slots and would give sufficient area. Both No. 6 round and square wires, however, are too large to fit well in the rather deep and narrow slots used in motors of this kind; therefore, two wires in parallel will be tried. No. 9 square wire has at least 15,000 circular mils after making allowance for rounding the corners so that they will not cut through the insulation. Two No. 9 square wires in parallel have 30,000 circular mils cross-section and will make a satisfactory conductor, provided they can be fitted into the slot. The winding will be two-layer, and since there are six conductors per slot, there will be three turns per coil, the wires being arranged as in Fig. 7.

Fig. 7

15. Dimensions of Slot.—No. 9 square wire measures .114 inch each way, and allowing for double cotton insulation, the over-all dimension each way will be .126 inch. The slot must be wide enough to contain two insulated wires side by side, and deep enough to contain six wires with

insulation all around. The width of the slot is determined as follows:

Insulation on each side of the conductors,

	INCH
One layer leatheroid	.012
One layer red rope paper	.006
One layer empire cloth	.008
Total for one side	.026
Two layers of conductor insulation, 2 × .026 .	.052
Two insulated No. 9 square wires, 2 × .126 .	.252
Total space necessary	.304

If the stator slots are made $\frac{5}{16}$, or .3125, inch wide, there will be .0085 inch clearance.

The slot pitch at the stator circumference is $\frac{24 \times 3.1416}{120} = .628$ inch; hence, the width of the tooth at the circumference is $.628 - .3125 = .3155$ inch. Fig. 8 shows the slot dimensions, together with the arrangement of the secondary slot and conductor, the dimensions of which will be determined presently.

Since the insulation of the primary winding overlaps on the coils, the total depth occupied by the two layers will be $2 \times (3 \times .126 + 3 \times .012 + 3 \times .006 + 3 \times .008) = .912$ inch. If the total depth of slot is made $1\frac{1}{32}$ inches, there will be

FIG. 8

room enough above the coils for a retaining wedge .05 inch thick, held in grooves as shown, and a clearance of .069 inch.

16. Depth of Iron Under Slots.—The stator core must carry half the flux per pole, or 1,050,000 ÷ 2 = 525,000 lines; and the area of the cross-section must be great enough to keep the flux density within safe limits. The maximum density might be as high as 47,000 or 48,000 lines per square inch in 60-cycle motors, but it is advisable to put in a liberal amount of iron back of the slots, especially if there is any probability of the same punchings being used for a smaller number of poles. The flux to be carried is not very large, so that even with a low density the extra amount of iron is not excessive. Taking a density of 35,000, the required cross-section is 525,000 ÷ 35,000 = 15 square inches. The core laminations have a spread of $7\frac{3}{4}$ inches, and assuming that 90 per cent. of this is iron, the radial depth required will be $\frac{15}{7.75 \times .9} = 2.15$, say $2\frac{1}{8}$, inches. The outside diameter of the stator punchings will be $24 + 2\left(1\frac{1}{32} + 2\frac{1}{8}\right) = 30\frac{5}{16}$ inches. The diameter at the bottom of the slots is $26\frac{1}{16} = 26.0625$ inches. The slot pitch at the bottom of the slot is $\frac{26.0625 \times 3.1416}{120} = .682$ inch. This will make the width of the tooth at the bottom .369 inch, approximately.

DIMENSIONS OF ROTOR

17. Air Gap and Outside Diameter of Rotor.—The clearance between stator and rotor will be made as small as mechanical considerations will permit, and for a rotor of 24 inches diameter, 35 mils = .035 inch will be about as close as it is safe to run. The outside diameter of the rotor will then be $24 - 2 \times .035 = 23.93$ inches.

18. Number of Rotor Slots and Size of Bar.—There is considerable choice as to the number of rotor slots, since a small number of large bars, or a large number of smaller bars can be used. In a given line of motors, the cross-

section of the rotor bars and slots is usually kept about the same in all the sizes—the total number of bars being larger or smaller, according to the output. The function of the rotor conductors is merely to provide a path for the induced currents, and theoretically it makes little or no difference what the ratio of transformation of the motor is. An extremely small number of conductors would lead to a poor design, since the heating due to copper loss would not be evenly distributed over the surface of the rotor. On the other hand, a very large number of bars would make the construction unnecessarily expensive. The number of rotor slots is nearly always purposely made different from the number in the stator, in order to avoid dead points at starting. Some authorities claim that the number of stator slots and the number of rotor slots should be prime to each other; but as this condition is not true with motors having wound rotors and as these motors always give good starting torque, this requirement does not seem to be essential. In the present design there are 120 stator slots, and satisfactory results will probably be obtained with 95 slots on the rotor.

19. Size and Shape of Rotor Conductors.—With a given stator current, the number of ampere-conductors on the rotor will be somewhat less than on the stator, because the stator current includes the magnetizing current. However, in figuring the size of rotor bar, the number of ampere-conductors may be considered the same on the rotor as on the stator, as this will be on the safe side.

The total ampere-conductors on the stator is equal to the number of slots times the conductor per slot times the current in the conductors, or $120 \times 6 \times 49.5 = 35{,}640$. The total number of rotor bars is 95, since the winding is of the squirrel-cage type having one bar in each slot. The current per conductor is therefore $35{,}640 \div 95 = 375$ amperes. The circular mils per ampere might be made somewhat less in the rotor than in the stator, because the insulation on the bars is very light and they can easily get rid of the heat; moreover, the core loss in the rotor is small, so that the

copper loss can be fairly high without the danger of excessive heating. However, there is usually sufficient room for a cross-section per ampere, at least as large as that on the stator, and making this allowance, 600 circular mils per ampere, the cross-section of the rotor conductors should be $375 \times 600 = 225{,}000$ circular mils, or 177,000 square mils, nearly. The slot pitch at the circumference of the rotor will be $\frac{23.93 \times 3.1416}{95} = .792$ inch.

20. Because of the low frequency in the rotor, the magnetic density in the teeth can be forced considerably higher than in the stator teeth. It is always advisable to make the slots as shallow as possible, thus bringing the conductor near the motor surface, decreasing the magnetic leakage, and improving the power factor. If the conductor is made $\frac{1}{2}$ inch wide, and 12 mils is allowed all around for insulation (one layer of tough paper), the total width will be $.5 + 2 \times .012 = .524$ inch. If the slots are made $\frac{9}{16} = .5625$ inch wide, there will be ample clearance for pushing the bars in from the end. The teeth will have overhanging lips, as shown in Fig. 8, while the projected width of a tooth at the circumference would be the slot pitch minus the width of slot or $.792 - .5625 = .2295$, say .23, inch.

The width of the bars is .5 inch = 500 mils; hence, for a cross-section of 177,000 square mils, the depth, or thickness, must be $177{,}000 \div 500 = 354$ mils. A bar $\frac{3}{8}$ inch thick gives 375 mils, or .375 inch, so this dimension will be adopted, as indicated in Fig. 8. This bar is slightly thicker than calculated, but after the corners are rounded the actual cross-section will be about 225,000 circular mils. The slot will be made $\frac{7}{16}$ inch deep at the edge of the tips, thus allowing room for a small fiber wedge to hold the bars firmly in place. The total depth from the bottom of slot to the circumference will be $\frac{7}{16} + \frac{3}{32} = \frac{17}{32}$ inch. The diameter at the bottom of the slots is $23.93 - 2 \times \frac{17}{32} = 22.87$ inches, approximately. The pitch at the tooth roots is $\frac{22.87 \times 3.1416}{95} = .7563$. The width

of the teeth at the roots is .7563 − .5625 = .1938, say .194, inch.

21. Depth of Iron Under Slots.—The magnetic density in the rotor core might be made quite high compared with the stator, because of the low frequency, but in order to secure a good construction mechanically and also to keep down the reluctance of the magnetic circuit, the same depth will be used as in the stator, namely $2\frac{1}{8}$ inches. This will make the inside diameter of the rotor punching 18.617 inches. By making the depth of iron 2.12 instead of 2.125 inches, the inside circumference can be made $18\frac{5}{8}$ inches.

22. Rotor End Rings.—Before the end rings can be proportioned, the approximate loss in them must be calculated. It has been previously explained that the total I^2R loss in the rotor for all practical purposes is the same percentage of the power delivered by the rotor as the slip is of the synchronous speed; also, that the I^2R loss and the slip must not be made too small, otherwise the motor will be deficient in starting torque. For a squirrel-cage motor of this output, the full-load slip will be about 4 per cent.; and since the output is to be 50 horsepower, the rotor I^2R loss will be approximately $50 \times 746 \times .04 = 1{,}492$ watts, or, in round numbers, 1,500 watts.

The spread of the laminations is $7\frac{3}{4}$ inches. Allowance should be made for a $\frac{1}{2}$-inch air duct in the center of the core and a $\frac{3}{8}$-inch duct at each end, making the over-all width between end heads 9 inches. The length of bar between centers of end rings, that is, the portion over which the current passes, will be at least 13 inches, allowing 2 inches at each end for the space taken up by the end heads and half the breadth of ring. The hot resistance of each bar is

$$\frac{\text{length in inches}}{\text{circular mils}} = \frac{13}{225{,}000}\text{ ohm}$$

As there are 95 bars and 375 amperes in each bar, the total loss in all the bars is $\dfrac{375^2 \times 13 \times 95}{225{,}000} = 772$ watts. The

two end rings must therefore be proportioned for a loss of 1,500 − 772 = 728 watts, or 364 in each ring.

From *Design of Alternating-Current Apparatus*, Part 3, the resistance of the ring between adjacent bars is

$$R = \frac{I^2 R \text{ loss in both rings}}{.2\, N_p^2\, I_b^2\, N}$$

In this case, N_p, the number of bars per pole, is 95 ÷ 10 = 9.5; I_b, the current per bar, 375 amperes; and N, the total number of bars, 95; hence,

$$R = \frac{728}{.2 \times (9.5)^2 \times (375)^2 \times 95}$$

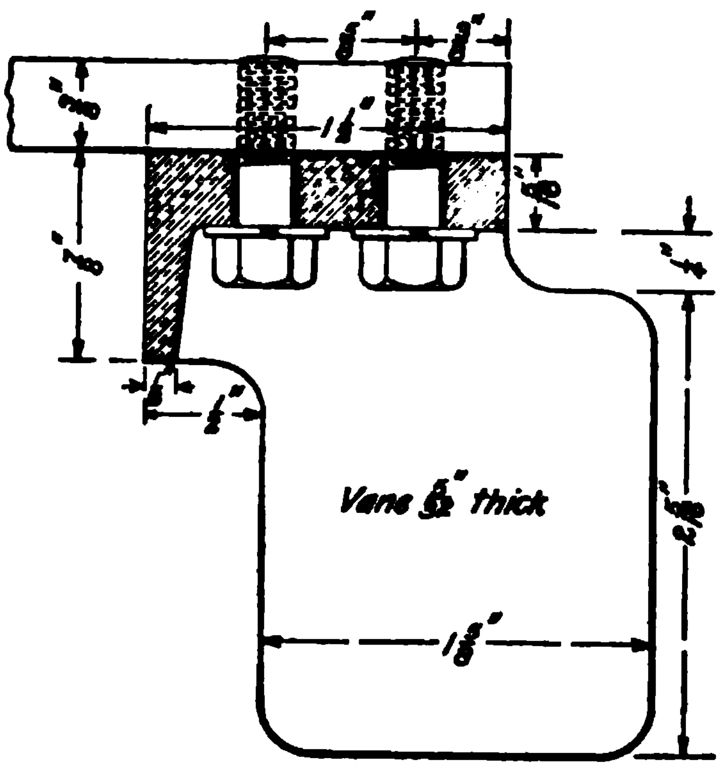


FIG. 9

23. The distance between centers of adjacent bars is, roughly, the same as the tooth pitch at the roots; that is, .756 inch. Since a large portion of the current flows from the parts of the bar near the edge, making the average path somewhat shorter than the distance between centers of bars, .7 inch will be a fair value to use. Assuming for the present that the rings are made of copper,

$$R = \frac{.7}{\text{circular mils}} = \frac{728}{.2 \times (9.5)^2 \times (375)^2 \times 95}$$

or, $$\text{circular mils} = \frac{.7 \times .2 \times (9.5)^2 \times (375)^2 \times 95}{728}$$

$$= 232{,}000, \text{ approximately,}$$

and 232,000 circular mils is equal to 182,000 square mils, or .182 square inch cross-section of copper.

The rings will be cast of a composition metal, the resistance of which will depend on the proportions of copper, zinc, etc. used. A good quality of cast brass can be made of an alloy having about three times the resistance of copper, and with this the cross-section must be .182 × 3 = .546 square inch.

The section will therefore be made as shown in Fig. 9. The width of the ring proper is 1½ inches, and the thickness

is $\frac{5}{16}$ inch, giving a cross-sectional area of $\frac{15}{32}$, or .469, square inch; the balance of the required cross-section is made up by a flange that projects downwards and stiffens the ring. Fan blades $1\frac{5}{8}$ inches wide, $2\frac{5}{16}$ inches deep, and $\frac{5}{32}$ inch thick are cast on the ring at intervals to promote ventilation. Each bar is bolted to the ring by two $\frac{1}{4}$-inch cap-screws provided with lock-washers.

CALCULATION OF LOSSES AND EFFICIENCY

STATOR RESISTANCE AND I^2R LOSS

24. To calculate the resistance of the stator windings, it is first necessary to lay out the shape of the coil and

FIG. 10

measure off the length of a mean turn; Fig. 10 shows the dimensions of one-quarter of a coil. Allowance is made for a duct $\frac{1}{2}$ inch wide in the center of the core, and one

$\frac{3}{8}$ inch wide at each end. There are twelve slots per pole, and one side of a coil goes into slot *1* and the other side of the same coil into slot *13*. The mean length of a turn as measured off the drawing is approximately 43 inches. There are forty slots per phase with six conductors or three turns per slot, making 120 turns per phase. The cross-section of the conductor (two wires in parallel) is 30,000 circular mils, and the hot resistance per phase is

$$\frac{\text{length (inches)}}{\text{circular mils}} = \frac{43 \times 120}{30{,}000} = .172 \text{ ohm}$$

The I^2R loss per phase is $49.5^2 \times .172$, and the total I^2R loss in stator is $49.5^2 \times .172 \times 3 = 1{,}260$ watts, approximately. This is the copper loss in the stator at full load. The copper loss in the rotor is already known, because the squirrel cage was designed for a slip of 4 per cent., or a loss of 1,500 watts. The total copper loss at full load is then $1{,}260 + 1{,}500 = 2{,}760$ watts.

IRON LOSSES

25. Loss in Stator Teeth.—To calculate the **iron losses**, the volume in cubic inches and the flux density in lines per square inch must first be calculated, and the loss per cubic inch determined from the curve given in *Design of Alternating-Current Apparatus*, Part 1. There are 120 stator teeth, and the dimensions, as shown in Fig. 8, are: mean width $= \frac{.315 + .369}{2} = .342$ inch; depth $= 1.0313$ inches.

Assuming that 90 per cent. of the spread of the laminations is iron, the volume of iron in teeth is $.342 \times 1.0313 \times 7.75 \times .9 \times 120 = 295$ cubic inches. There are twelve slots per pole, and the average cross-section of teeth under one pole is $.342 \times 7.75 \times .9 \times 12 = 28.6$ square inches. The flux per pole is 1,050,000 lines; average tooth density, $\frac{1{,}050{,}000}{28.6}$; and maximum tooth density, $\frac{1{,}050{,}000}{28.6 \times .636} = 58{,}000$ lines per square inch. At this density, the loss is about 1.05 watt per cubic inch for a frequency of 60 cycles. The total loss in the teeth is $295 \times 1.05 = 310$ watts.

26. Loss in Iron Under Slots.—The diameter of the core at the bottom of slots is $24 + 2 \times 1\frac{1}{32} = 26\frac{1}{16} = 26.0625$ inches. The outside diameter of core is $26\frac{1}{16} + 2 \times 2\frac{1}{8} = 30\frac{5}{16} = 30.3125$ inches. The volume of core under slots is $\frac{1}{4} \times 3.1416 \times (30.3125^2 - 26.0625^2) \times 7.75 \times .9 = 1{,}312$, say 1,320, cubic inches.

The density in this part of the iron has been made 35,000, and the loss per cubic inch will be about .4 watt, thus making the total stator core loss $1{,}320 \times .4 = 528$ watts. The iron loss for the stator teeth and core will then be $310 + 528 = 838$ watts. The iron loss in the rotor will be very small because of the low frequency, so that 900 watts will be a fair allowance for iron losses in both stator and rotor.

27. Full-Load Efficiency.—At full load, the electrical losses will be as follows:

	Watts
$I^2 R$ loss (stator and rotor)	2,760
Core loss	900
Total loss	3,660

To allow for windage and friction, the total loss will be taken as 3,900 watts. The output at full load is $50 \times 746 = 37{,}300$ watts, and the input at full load is $37{,}300 + 3{,}900 = 41{,}200$ watts. The full-load efficiency is therefore $37{,}300 \div 41{,}200 = .905$, or 90.5 per cent. This is somewhat above the specified efficiency of 89 per cent.

MAGNETIZING CURRENT

28. By the formula given in *Design of Alternating-Current Apparatus*, Part 3, the magnetizing current

$$I_o = \frac{p\,\Phi\,l'_g}{1.7\,m\,T_p\,T\,l}$$

In this case, the number of poles $p = 10$; the flux per pole $\Phi = 1{,}050{,}000$; the effective length of air gap $l'_g = .035 \times .628 \div .3125 = .07$ inch, approximately; the number of phases $m = 3$; the number of turns per phase $T_p = 120$;

the pole pitch $T = 7.54$ inches; and the length of core parallel with the shaft $l = 7.75$ inches. Then, the magnetizing current

$$I_e = \frac{10 \times 1{,}050{,}000 \times .07}{1.7 \times 3 \times 120 \times 7.54 \times 7.75}$$
$$= 20.6 \text{ amperes, approximately}$$

This is the magnetizing, or wattless, component of the no-load current. The power, or watt, component is that required to supply the no-load losses, and the resultant of the two is the current that the motor takes when running idle. Since the idle current is very nearly the same as the magnetizing current, the stator I^2R loss at no load will be about $20.6^2 \times .172 \times 3 = 220$ watts, approximately. The I^2R loss in the rotor is negligible at no load. Core loss, windage, and friction will be about $3{,}900 - 2{,}760 = 1{,}140$ watts (see Art. **29**), making the total no-load loss $1{,}140 + 220 = 1{,}360$ watts. At 550 volts, this would call for a line current of $\frac{1{,}360}{550 \times \sqrt{3}} = 1.43$ amperes.

The no-load current is therefore the resultant of a wattless component of 20.6 amperes at right angles to the electromotive force, and a watt, or power, component of 1.43 amperes in phase with the electromotive force, thus making the current taken from the line at no load equal to $\sqrt{(20.6)^2 + (1.43)^2} = 20.65$ amperes, approximately.

CIRCLE DIAGRAM

LEAKAGE FACTOR

29. The **leakage, or dispersion, factor** is found from the relation

$$\text{leakage factor} = \frac{\text{air gap}}{\text{pole pitch}} \times C$$

The value of the coefficient C, as previously explained, usually lies between 10 and 20, and its probable value in any given case is, as a rule, fixed with a fair degree of

accuracy from the designer's knowledge of the performance of similar machines. A fair value for a motor such as the one under consideration is 12.5. This gives

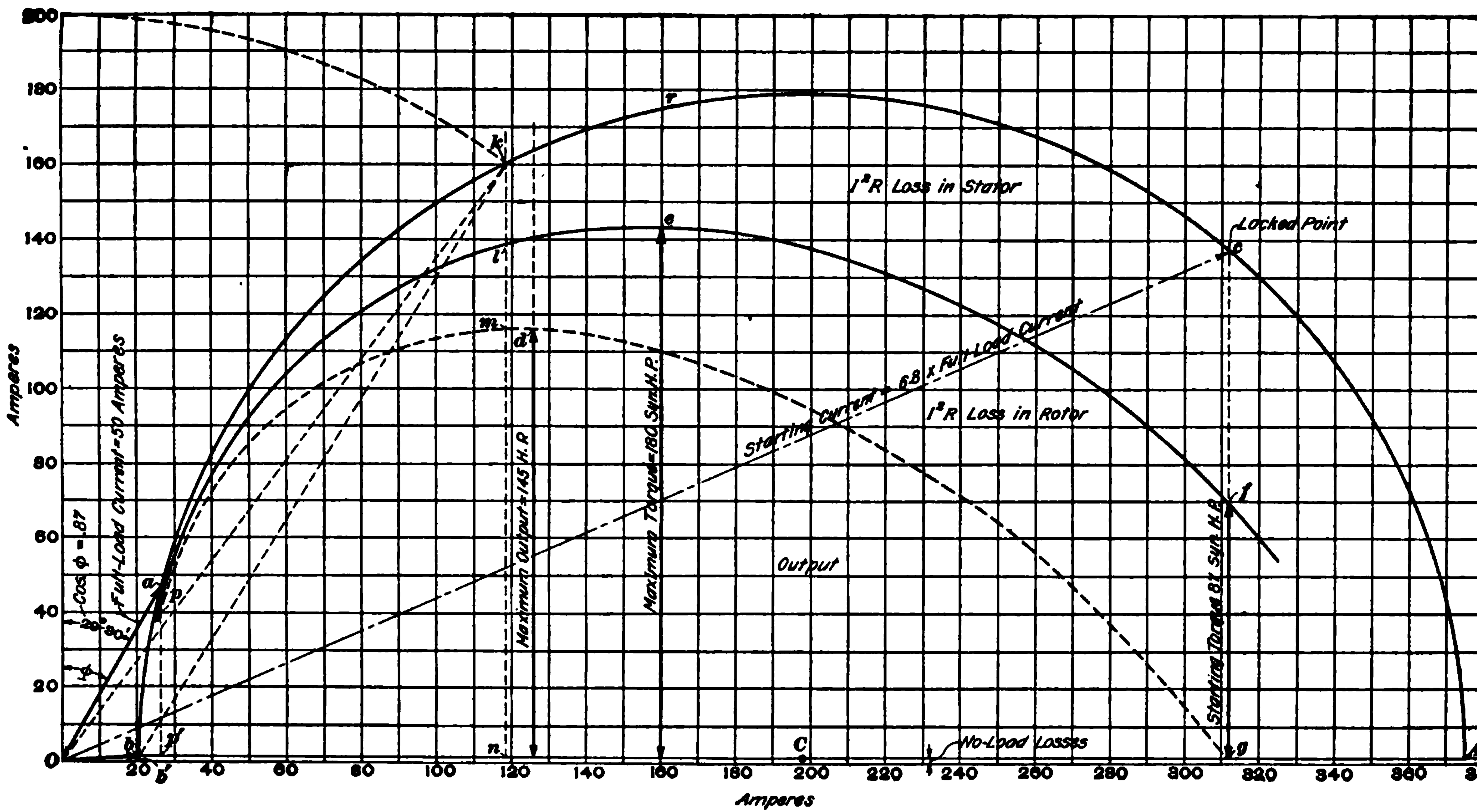
$$\text{leakage factor} = \frac{.035}{7.54} \times 12.5 = .058, \text{ approximately}$$

CONSTRUCTION OF DIAGRAM

30. All the data required for the construction of a circle diagram have been obtained. The magnetizing component of the no-load current is 20.6 amperes, and the power component 1.43 amperes. Hence, in Fig. 11, calling each division 10 amperes, lay off $O b' = 20.6$ amperes and $b b' = 1.43$ amperes. The no-load current is then represented by the line $O b$, which is nearly 90° from the vertical line through O representing the direction of the applied electromotive force. Through the extremity b of $O b$ draw a horizontal line $b A$ parallel with the base line; the center C of the circle lies on this line and the diameter is found from the relation

$$\text{diameter of circle} = \frac{\text{magnetizing current}}{\text{leakage factor}} = \frac{20.6}{.058}$$
$$= 355 \text{ amperes}$$

31. Taking a radius equivalent to $\frac{355}{2} = 177.5$ amperes, and with a center C on line $b A$, describe a semicircle $b a k A$. By means of this semicircle, the current that the motor will take under different load conditions may be found. The distance between line $b A$ and the horizontal base line represents the no-load losses in watts expressed as so much current, that is, 1,360 watts, or 1.43 amperes on a three-phase circuit at 550 volts. The ordinates between the semicircle and the line $b A$ are proportional to the total input less the no-load losses, and by subtracting the copper loss in stator and rotor for each value of the current, the output is obtained. For example, point k corresponds to the large current $O k = 200$ amperes. The primary resistance per phase is .172 ohm, and the $I^2 R$ loss corresponding to



I²R Loss in Stator
Locked Point
I²R Loss in Rotor
Starting Current = 6.8 x Full Load Current
Output
Maximum Output = 145 H.P.
Maximum Torque = 180 Syn. H.P.
Starting Torque 81 Syn. H.P.
No-Load Losses
Full-Load Current = 50 Amperes
Cos φ = .87
29° 30'
Amperes
Amperes

Fig. 11

200 amperes is $200^2 \times .172 \times 3 = 20{,}640$ watts; this is equivalent to $\frac{20{,}640}{550 \times \sqrt{3}} = 21.7$ amperes, approximately, and subtracting 21.7 from the ordinate of point k gives point l. The ordinate $l\,n$ represents the power supplied to the rotor, and from $l\,n$ must be subtracted the loss in the rotor to obtain the output.

The rotor has been designed so that with a current of 375 amperes per bar the total loss is 1,500 watts. The loss at any other rotor current I_x will be $\frac{I_x^2}{375^2} \times 1{,}500$. The rotor current corresponding to the point k is represented in terms of the primary current by line $b\,k$, which scales 186 amperes. The primary has 120 slots with six conductors per slot, making 720 conductors in all. The rotor has 95 conductors, hence the actual current in the rotor is $186 \times \frac{720}{95} = 1{,}410$ amperes, nearly. The loss in the rotor corresponding to this current is $1{,}500 \times \frac{1{,}410^2}{375^2} = 21{,}200$ watts, nearly. With a three-phase supply at 550 volts, this is equivalent to a current of $\frac{21{,}200}{550 \times \sqrt{3}} = 22.3$ amperes, approximately. In Fig. 11, $l\,m$ is therefore laid off to scale 22.3 amperes, thus giving the useful output $m\,n$.

In this example, point k corresponds to a current very much in excess of that at normal full load, and the I^2R losses are correspondingly exaggerated. If, for several different points on the semicircle, the primary I^2R loss in amperes at 550 volts is calculated and subtracted from the ordinates of the semicircle, the curve $l\,e\,f$ will be obtained; and if from the ordinates of this curve the corresponding rotor losses in amperes are subtracted, curve $p\,m\,g$ will be obtained. The ordinates measured between curve $l\,e\,f$ and the line $b\,A$ are proportional to the input of the rotor, and hence that of the torque; those measured between curve $p\,m\,g$ and the line $b\,A$ are proportional to the output.

32. When current Oc is reached, the stator and rotor losses become so great that, taken together, they are equal to the total watt input cg. The motor is therefore at a standstill; that is, Oc is the motor current with the rotor locked, or held from turning, and full voltage applied to the terminals. Also, Oc is the current that would be drawn from the line at the moment of starting if full voltage were applied. In this case, the current is about 6.8 times normal full-load current, which is represented by the length of line Oa. The full-load current Oa is found as follows: For the required output of 50 horsepower, the watt, or actual, power component of the current must be $\frac{50 \times 746}{550 \times \sqrt{3}} = 39.2$ amperes, nearly. Find point p on the curve pmg such that the ordinate pp' between it and the horizontal line bA is equal to 39.2 amperes. Point a on the semicircle vertically above p fixes the full-load current Oa, the distance pa being proportional to the combined stator and rotor I^2R losses at full load.

33. Full-Load Power Factor.—As measured on the diagram, the angle ϕ by which the full-load current lags behind the electromotive force is 29° 30′. The full-load power factor cos ϕ is therefore .87. This is somewhat under the power factor specified, but the difference is hardly great enough to warrant the use of a larger diameter or smaller air gap in order to secure a lower leakage factor, especially since the actual leakage factor may vary somewhat from the calculated value. The calculated efficiency is .905 and the power factor .87, giving an apparent efficiency of $.905 \times .87 = .787$. The specified efficiency is .89 and the power factor .89, making the apparent efficiency. $.89 \times .89 = .792$. It is the apparent efficiency that determines the current input, and while the motor designed is a trifle low in power factor, it is higher than the specifications for efficiency, making the apparent efficiency very nearly what was specified. If it were necessary to adhere rigidly to specifications, another design would have to be worked out.

The full-load current, as obtained from the diagram, is 50 amperes, approximately.

34. Starting Torque.—At starting on full voltage, the total watt input is proportional to cg, Fig. 11, the loss in the stator to cf, and the input supplied to the rotor to fg; line fg is therefore proportional to the torque developed in the rotor. This line scales 68 amperes, which corresponds to $\frac{68 \times 550 \times \sqrt{3}}{746} = 87$ horsepower, nearly; that is, if the same torque were developed at synchronous speed, the output would be 87 horsepower. The torque is therefore expressed in terms of synchronous horsepower instead of pounds at 1 foot radius, as with direct-current motors. Since the full-load speed is very little less than the synchronous speed, the starting torque is about $\frac{87}{50} = 1.7$ times full-load running torque. In other words, if full voltage were applied to the motor terminals, it would take a current about 6.8 times full-load current and give about 1.7 times full-load torque. If the torque required to start the motor exceeded this amount, the motor would not start. On the other hand, if the motor had to start on a light load, the voltage applied to the stator could be reduced, thereby cutting down the large starting current. This is usually done by means of autostarters, compensators, or potential starters, as they are variously called, the applied voltage being reduced by means of autotransformers. Since the starting current depends on the applied voltage, and the torque is proportional to the product of the current and the voltage, the starting torque is proportional to the square of the applied voltage.

35. Maximum Torque.—The motor exerts its **maximum torque** when it is loaded to the point r, Fig. 11, on the circle bkA, because at this current the ordinate of the curve bcA reaches its maximum value. If loaded beyond this point, the motor would stop; hence, this is called the *pulling-out point* of the motor. In this case, since the current Or is so much in excess of normal full-load current Oa,

the windings would be greatly overheated before the pulling-out point was reached. By scaling off the ordinate from the point *e* and calculating as before, the synchronous horsepower is found to be 180; that is, the motor will deliver a torque of approximately 3.6 times full-load torque without stopping. A high overload pulling-out point is a desirable feature in an induction motor, especially if it is subjected to heavy momentary overloads or if the line voltage is likely to drop below normal at times.

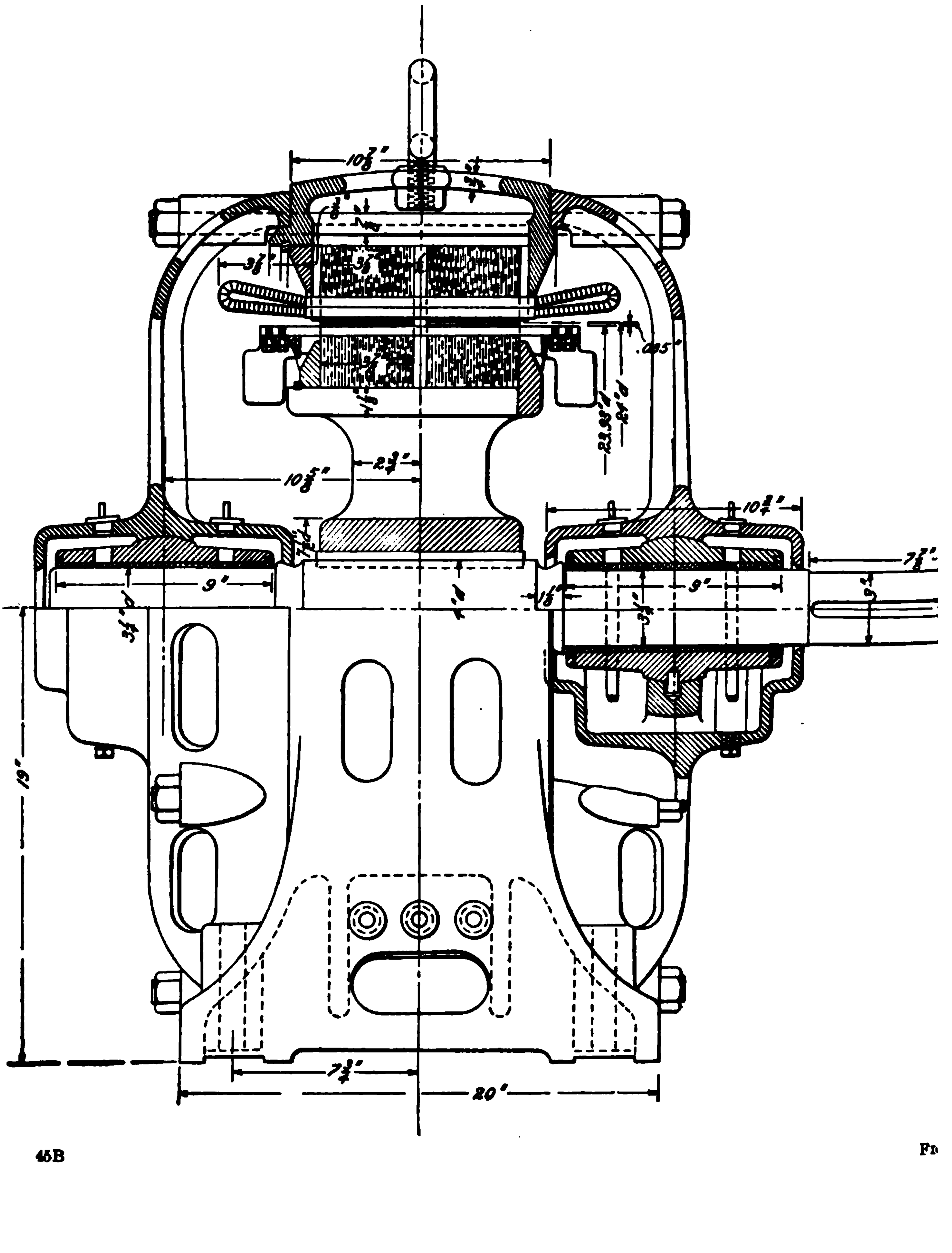
36. Maximum Output.—The **maximum output** that the motor can deliver is given by the ordinate of the dotted curve *bdg* at *d*, Fig. 11, because at this point the curve reaches its maximum height. This corresponds to an output of 145 horsepower, or nearly three times full load.

37. General Performance.—The general performance of the motor, as thus determined from the circle diagram, shows that the overload capacity, starting torque, and maximum output are satisfactory for a motor of this type. The slip will be 4 per cent. at full load, and for lower loads will decrease in direct proportion.

If a very large torque were required at starting, the rotor would be provided with a regular three-phase winding and with collector rings. By using rotor starting resistance, such that point *c*, Fig. 11, is shifted back to *r*, the maximum starting torque of 180 synchronous horsepower would be obtained with a starting current *Or*.

DETAILS OF CONSTRUCTION

38. The mechanical construction of the motor just calculated is shown in Fig. 12. The details might be modified in a number of ways without affecting the durability or the performance, but the design shown is such as is suitable for a motor of this size. The stator punchings are supported in a cast-iron yoke provided with numerous ventilating openings and faced off at each side to receive the end housings that carry the bearings. In this case, the end housings are split, thus allowing the use of self-alining



45B

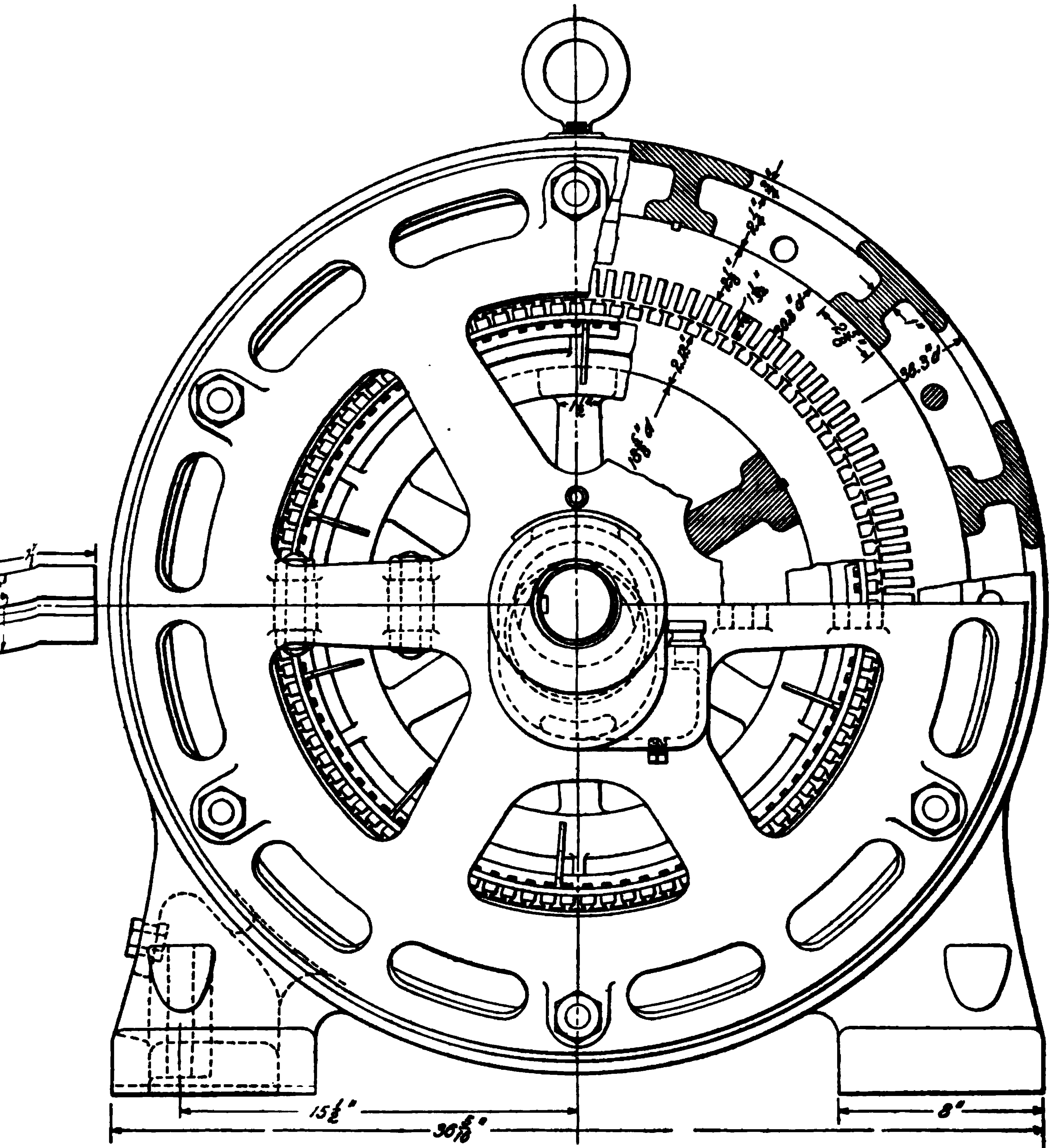


FIG. 12

ball-and-socket bearings. In many cases, however, the housings are in a single piece, the bearing sleeves being straight. The sleeves are of cast iron lined with Babbitt metal; oiling is effected in the usual manner by rings dipping into an oil reservoir. Holes are provided 30° apart in the stator yoke, through which pass six bolts that hold the bearing housings securely in place; these bolts allow the housings to be shifted through 90° in case the motor is to be attached to a side wall, or through 180° for ceiling suspension. Bearings on such motors usually have a length from two and one-half to three times their diameter. The journals in this case are $3\frac{1}{4}$ in. $\times$ 9 in.; the shaft has a diameter of 4 inches at the center.

The rotor punchings are carried on a six-armed cast-iron spider and are clamped between the head and an end plate, which is held in place by a split ring inserted after the plate has been pressed into place. The end rings of the squirrel cage are supported on projections on the end heads.

The stator winding requires no special description; it is of the two-layer type, with four coils per pole per phase. The three terminals are brought out through soft-rubber bushings in one of the stator feet.

TRANSFORMERS

LIMITATION OF OUTPUT

39. The primary winding of a transformer is the one to which current is supplied, and the secondary winding the one from which current is delivered. Since all transformers may be used to step the voltage up or down, either the primary or the secondary may be the high-voltage coil. The most common arrangement, and the one here understood, is to connect the primary winding to the high-voltage circuit. The losses in a transformer, with the exception that there is no loss due to windage and friction, are the same as those in a generator or motor; namely, copper loss (I^2R loss) and iron, or core, loss. Serious copper loss occurs only while the transformer is loaded, and increases in

proportion to the square of the current; iron loss exists as long as electromotive force is applied to the primary, and alternating magnetism thereby set up in the core, whether the transformer is loaded or not. If a transformer is to be loaded for only a small part of the day, as, for example, in lighting work, it should be designed for small iron loss, even if the copper loss has to be made comparatively large.

The losses develop heat in the windings, thus raising the temperature and fixing a limit beyond which it is not safe to increase the load. Transformers are usually immersed in oil in a cast-iron or sheet-metal case; the oil provides thorough insulation and serves to conduct the heat from the coils and core to the case, where it is given off to the surrounding air. By providing the case of small transformers (up to about 250 kilowatts) with deep corrugations, there is no difficulty in obtaining enough cooling surface; but the surface of the large sizes would have to be very great to get rid of the heat, and special means are adopted for cooling by means of water circulation or air blast. The practical limitation in output is therefore the heating effect, no matter what the type of transformer may be. Aside from the heating, however, it is not advisable to force a transformer much beyond its rated load, because the efficiency decreases and the voltage drops to an extent that may prove undesirable, particularly if incandescent lights are supplied.

FEATURES OF DESIGN

EFFICIENCY

40. The **efficiency** of a well-designed transformer should be high not only at full load, but throughout a wide range in load. This is specially desirable if the transformer works on a fluctuating load. With a given impressed electromotive force, the primary must generate a back electromotive force practically equal to the impressed. Now, the induced back electromotive force is proportional to the

product of the flux and the turns, and a transformer can be designed with a comparatively small flux and a large number of turns, making the copper loss high, or with a large flux and a small number of turns, making the iron loss comparatively high. In either case, the total loss might be the same, and one transformer may give as high full-load efficiency as the other. If the output remains steady at or near full load during the greater part of the time, as, for example, with transformers used for supplying power, it is an advantage, because of better regulation, to have the copper loss relatively small.

Fig. 13 shows the approximate full-load efficiency obtained

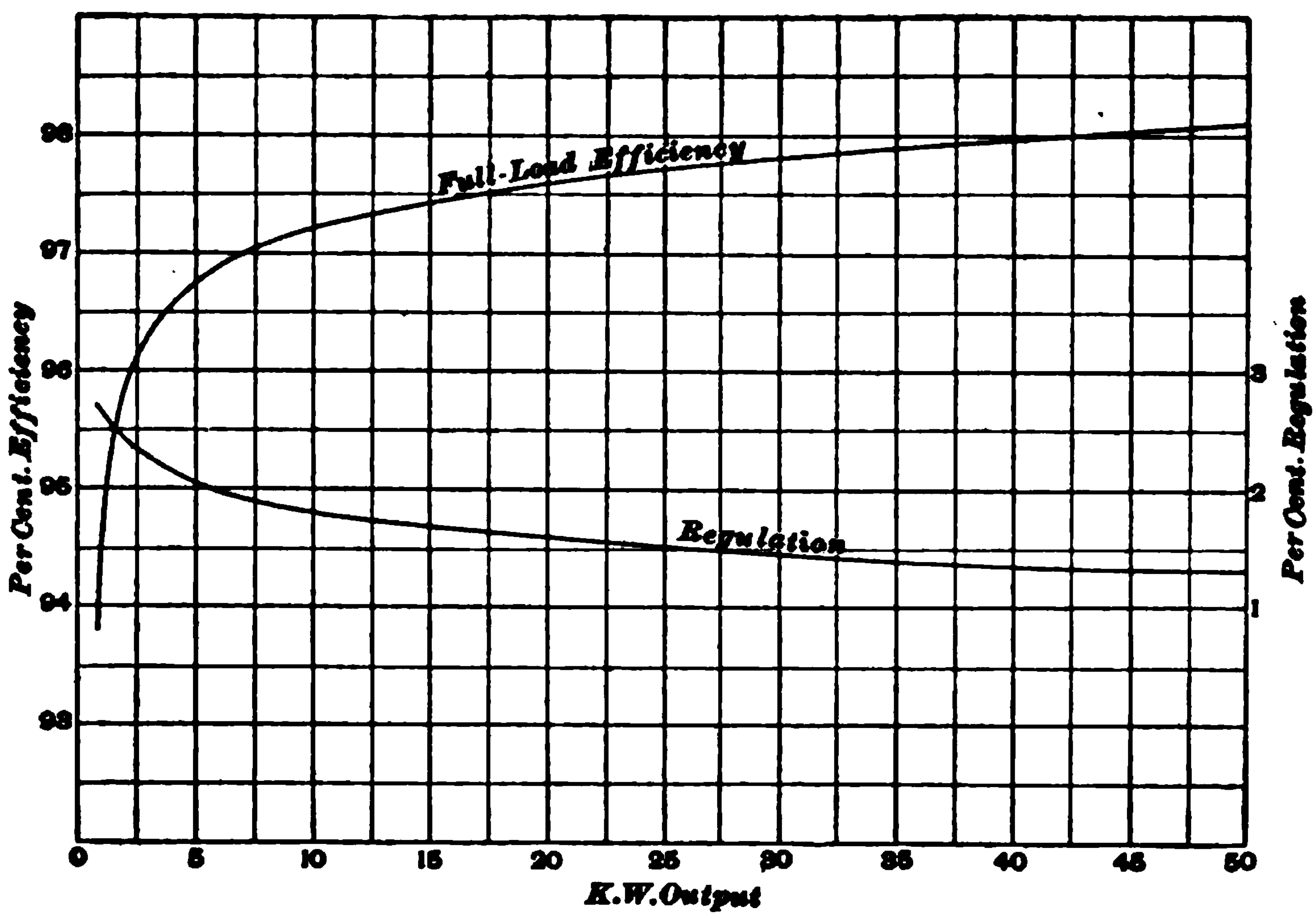


FIG. 13

in commercial transformers of good design. In the larger sizes, an efficiency of over 98 per cent. is obtained.

REGULATION

41. By **regulation** of a transformer is meant the percentage increase in voltage when full load is thrown off the secondary. When a transformer is loaded, there is always

a certain falling off in secondary voltage, and when the load is thrown off, the voltage rises, the action being similar to that already explained in connection with alternators. The regulation of a good transformer, however, is much closer than that of an alternator, being seldom over 3 per cent. on non-inductive load or over 6 per cent. on inductive load of power factor .8. Fig. 13 shows the approximate regulation obtainable with transformers of good design operating on non-inductive load.

42. The voltage drop is caused by the passage of current through the resistance and inductance of the windings. The resistance drop is usually small if a liberal allowance of copper has been made in the windings. The inductive drop, caused by the alternating magnetism that leaks between the primary and secondary coils, can be limited in two ways; namely, by subdividing the primary and secondary coils and interleaving them, thus reducing the leakage flux, or by using a comparatively large working flux in the transformer, and thereby having a correspondingly small number of turns in the primary and secondary coils with which the leakage flux may link. In case the transformer works on an inductive load, as, for example, induction motors, and if good regulation is desired, it is important to limit the inductive drop, because with a lagging current this has a relatively large effect on the terminal electromotive force, as explained in connection with the regulation diagrams for alternators.

GENERAL ARRANGEMENT OF COILS

43. Fig. 14 shows the general arrangement of the coils and core of a shell-type transformer, with the primary *P* and secondary *S* made of thin, flat coils interleaved. The core *a b* is made of strips assembled so as to overlap at the corners and form a continuous magnetic circuit. Fig. 15 shows two coils, or sections, for the primary of a power transformer. These coils are wound with flat cotton-covered strip, and after completion are taped as shown by the right-hand coil.

In small core-type transformers, the primary and secondary are also wound in sections, usually two sections for each.

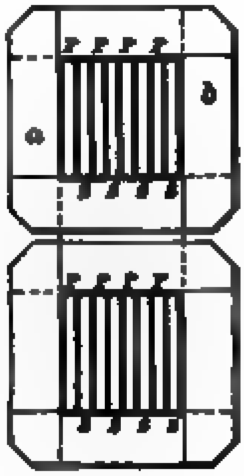


Fig. 14

The transformer is assembled with one primary and one secondary section on each leg of the core.

The interleaving of the coils, to reduce magnetic leakage and at the same time secure better insulation, is shown in

Fig. 15

Fig. 16, which illustrates a portion of the assembled coils for a Bullock power transformer. The primary sections *P*

are usually more bulky than the secondary sections S, because they contain many more turns and the space occupied by insulation is greater. Between the primary and secondary sections are interposed insulating shields, which are usually made of fullers' board or similar material and composed of several layers fastened together. Similar shields are placed between adjacent sections of the primary, in case a high difference of potential exists between them. These insulating barriers should extend beyond the edges of the coils. Spacing strips a of specially treated wood are placed as shown, to form ducts through which the oil surrounding the windings can circulate freely and carry off the heat. Insulating material b is wrapped around the primary sections, and the assembled coils are held together by taping c at the sides. The terminals of the primary coils are marked P' and the terminals of the secondary coils S'.

Fig. 16

Fig. 17 shows the coils and core of a larger size of power transformer that is partly assembled, and indicates the method of building up the core around the coils. A layer

Fig. 17

of insulating material *a a* is placed around the coils next to the iron, and sticks *b* are spaced around to form a channel between the coils and the iron, thus ventilating the core.

DIVISION OF LOSSES

44. Fig. 18 shows the relative values of core loss and copper loss in ordinary core-type transformers of good design intended for operation on lighting circuits with frequencies varying from 50 to 140 cycles per second. Two curves for

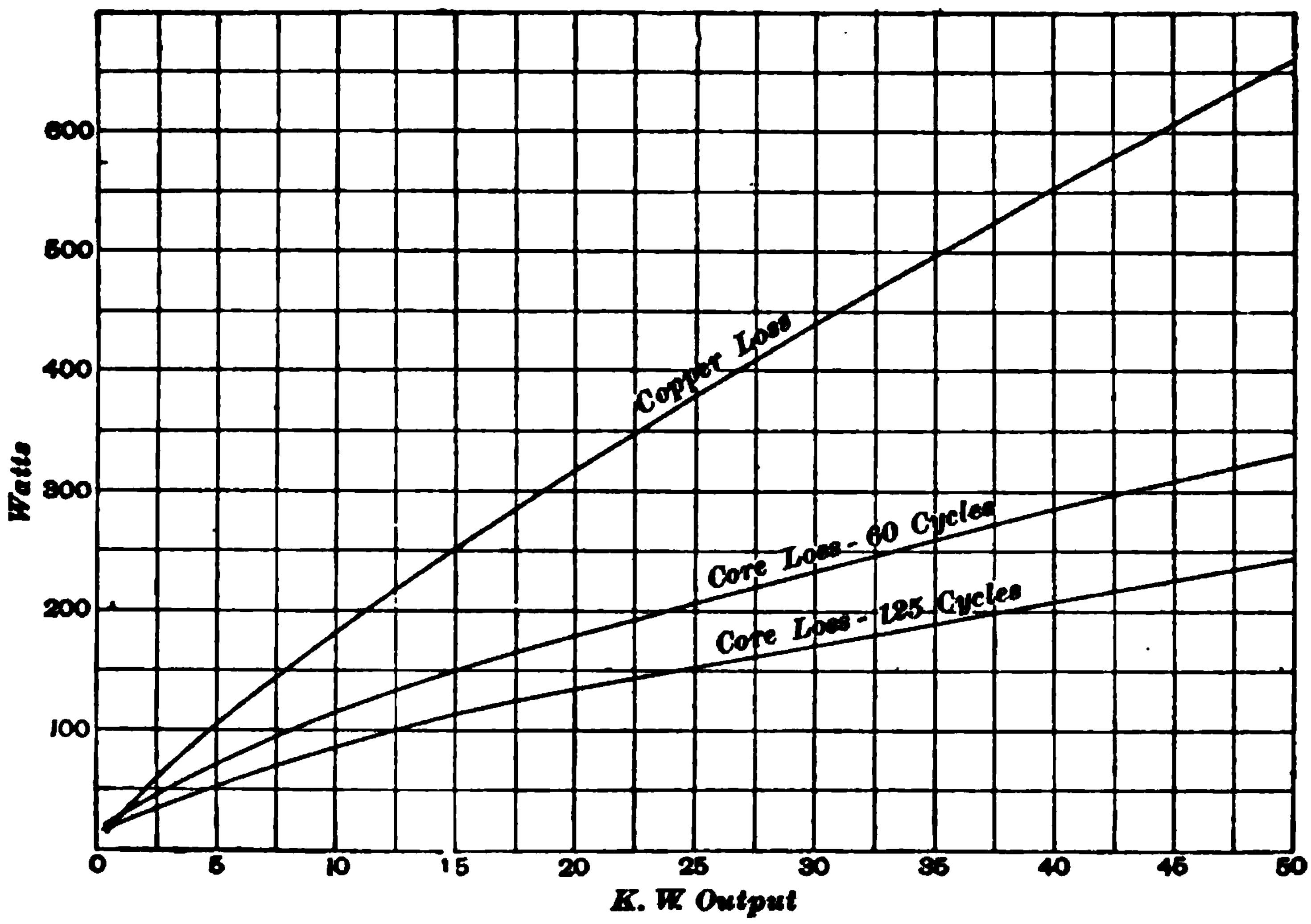


FIG. 18

core loss are given, one at 60 cycles and the other at 125 cycles. The core loss at the lower frequency is of course the higher, because, with the same applied voltage, the magnetic density must be over twice as great. The copper loss is relatively large, being about twice as great as the iron loss at 60 cycles in sizes above 25 kilowatts. The copper loss of power transformers is not often greater than the iron loss, and is frequently as low as 70 to 75 per cent. of the iron loss. In designing lighting transformers, therefore, the losses should be apportioned about as shown in

Fig. 18, and this implies a comparatively small amount of iron, a small flux, and a large number of turns. The combined iron and copper losses of power transformers is about the same as that for lighting transformers, but the core loss is increased by using a relatively large volume of iron for a large working flux, and the copper loss is decreased by using a comparatively small number of turns.

MAGNETIC FLUX AND ELECTROMOTIVE FORCE

45. In a transformer, the relation between the electromotive force E, turns T, flux Φ, and frequency n is

$$E = \frac{4.44\,\Phi\,T n}{10^8} \qquad (1)$$

This relation holds for either primary or secondary, E and T being taken in all cases for the same coil of the transformer.

FIG. 19

In setting out to design a transformer, the primary electromotive force E_p and the frequency n are known; hence, the product of flux and primary turns may be determined by the formula

$$\Phi\,T_p = \frac{E_p \times 10^8}{4.44\,n} \qquad (2)$$

Any combination of flux and turns that will satisfy this formula will be satisfactory so far as the generation of the back electromotive force is concerned; and, if either the flux or the turns are known, the other can be calculated.

There is considerable range in values of the flux or turns that may be used for a transformer of given output and frequency, and no hard-and-fast rule can be given for the selection of either; the values chosen might vary considerably and yet give satisfactory designs. However, as a general guide, Figs. 19 and 20 are given to show suitable values of

Φ = Flux (Megalines)

K.W. Output

FIG. 20

the flux Φ, Fig. 19 being for 60-cycle core-type lighting transformers, and Fig. 20 for shell-type power transformers for both 60 and 25 cycles. In each case, the abscissas represent secondary output in kilowatts, and the ordinates, flux in megalines (1 megaline = 1,000,000 lines). Power transformers for 25 cycles are necessarily worked with a higher flux than those for 60 cycles, otherwise, with the low frequency, the number of turns would be too large.

MAGNETIC DENSITIES

46. **The magnetic density** in transformer cores is rather low, especially in those for operation on 60 cycles. On 25 cycles, the density can be run higher without causing too large a core loss. In small 60-cycle lighting transformers, the core density is usually from 35,000 to 40,000 lines per square inch; in large 60-cycle power transformers, it may be from 45,000 to 55,000; and in 25-cycle power transformers, from 65,000 to 75,000.

CURRENT DENSITIES

47. In transformers, there are no moving parts to set up air-currents to carry off the heat; therefore, a circulation of oil or air is maintained for that purpose. Because of the difficulty of dissipating the heat losses, and also because the losses must be made small in order to obtain a high efficiency, a liberal cross-section per ampere must be allowed in the primary and secondary conductors. In small core-type lighting transformers, the circular mils per ampere in the primary may be from 1,000 to 1,800, and in the secondary, from 1,200 to 2,000. The space occupied by insulation in the secondary is smaller than in the primary, and a more liberal cross-section per ampere can be allowed without making the secondary occupy any more room than the primary. In large power transformers, the circular mils per ampere in the primary may be from 1,000 to 1,500, and in the secondary, from 1,200 to 1,800.

48. **Form of Conductor.**—In small transformers, the primary conductor usually consists of round, double cotton-covered wire; the secondary conductor may be of wire or rectangular strip, depending on the current-carrying capacity required. In large power transformers, the conductor for both primary and secondary can usually be made of strip, and the thin, flat coils wound up with but one turn per layer. If the transformer is to operate on very high voltage, it may be necessary to use wire for the primary winding.

METHODS OF COOLING

49. There are three common methods of cooling transformers; namely, by direct radiation and conduction to the air; by water circulation; and by air blast.

In the first two methods, the transformer windings and core are immersed in oil held in a tank made of cast iron, boiler plate, or sheet iron. In the last method, the transformer is placed over an air chamber in such manner that a blast of air can be forced through it, thus carrying off the heat.

50. Self-Cooled Transformers.—Where direct radiation and conduction are depended on to dissipate the heat, the case containing the windings, core, and oil should be designed to present a large surface to the air. For small lighting transformers, plain cast-iron cases provide sufficient cooling surface; but on the larger sizes, the case is generally corrugated to increase the cooling area. In order to limit the temperature rise to 40° C., the outer surface of the case should present from 8 to 12 square inches of cooling surface for each watt lost in the transformer.

51. Water-Cooled Transformer.—A **water-cooled transformer** is one that has coils of pipe within the oil tank and around the windings, through which cold water is circulated. For such transformers, plain boiler-plate cases are generally used, because the water is depended on to carry off the heat, and a large cooling surface on the case is not necessary. A coil of seamless copper tube is mounted in the upper part of the tank, so that it comes just below the oil level, and a continuous circulation of cold water is maintained through the coil. If the entering water is at a temperature of 15° to 20° C., $\frac{1}{8}$ to $\frac{1}{4}$ gallon per minute per kilowatt loss in the transformer is sufficient to carry off the heat. If, however, the inside or outside of the tubes becomes coated with a deposit or sediment of any kind, the cooling action will be greatly impaired, and it may be impossible to keep down the temperature of the transformer no matter how much water is forced through.

52. Air-Blast Transformers.—In **air-blast transformers** there is no oil to depend on for high insulation, and it is therefore very difficult to build these for pressures above 30,000 volts; even at this pressure there is danger from brush discharges and creepage over the insulation, unless the design is good and the whole construction very carefully carried out. However, for pressures below 25,000 volts, air-blast transformers are much used. The amount of air required for cooling is from 150 to 200 cubic feet per minute for each kilowatt loss in the transformer. The air is usually supplied at a pressure of from ½ to 1 ounce per square inch, and is furnished in most cases by motor-driven blowers.

TRANSFORMER INSULATION

INSULATION OF THE WINDINGS

53. It is essential that the insulation of transformers be of a very high grade, as they are usually subjected to high electromotive force. It is by no means uncommon to insulate transformer windings for pressures as high as 70,000 or 80,000 volts. The primary and secondary coils must be thoroughly insulated from each other and from the core, and all internal parts between which a high potential exists must be well separated by insulating material. In high-pressure transformers immersed in oil, the oil is mainly depended on to furnish the necessary insulation, though diaphragms of fullers' board or other similar material are inserted between the coils. In air-blast transformers, the insulation must be capable of withstanding the pressure without any aid from oil, and the coils must be well separated by diaphragms of high dielectric strength.

In large transformers, the electromotive force between adjacent turns of a coil may be considerable, even if there is only one turn per layer. Extra insulation, in addition to the cotton covering on the conductor, is provided by winding one or more layers of pressboard or paper between each two layers of the coil.

The secondary conductor is usually made up of several bare strips in parallel, in order to secure flexibility and also to prevent eddy currents. When this is the case, thin paper should be placed between the layers, otherwise the advantage of laminating the conductor to reduce eddy currents may be largely lost.

Transformers must be capable of withstanding a test of twice the normal voltage of the high-voltage winding applied between primary and secondary or between primary and core. These tests should be made after the transformer has been warmed up by a heat run at full load. The insulation must therefore be designed to stand at least twice normal voltage, with a liberal margin of safety. Fullers' board in thin sheets should stand about 400 volts per mil before breaking down; for example, a sheet .01 inch thick would stand about 4,000 volts. Much, however, depends on the amount of moisture in the material, and care should be taken that all insulating material is thoroughly dried out.

54. Transformer Oil.—Mineral oils used for insulating purposes are obtained from crude petroleum; animal or vegetable oils are not used for this purpose. A good transformer oil must have a high dielectric strength; that is, it must be able to stand a high electromotive force without breaking down. This oil must be free from moisture; a very small amount of moisture will lower the dielectric strength greatly and make an oil that is in reality a good insulator appear to be a very poor one. The oil must not form a deposit when held continuously at the working temperature of the transformer; some oils throw down a gummy kind of deposit that coats the cooling coils and eventually clogs up the circulating ducts in the transformer, thus interfering greatly with the cooling. The oil should have a high flashing point, otherwise it will catch fire too easily. The flashing point must be well above the working temperature of the transformer, even when the latter is subjected to prolonged overloads. It is also desirable that the oil be rather thin, so that it will circulate freely and carry off the heat

from interior parts. No acid should be contained in the oil, and it is desirable, though not essential, that the oil be of light color. If the oil is light-colored, the presence of dirt

Fig. 21

or of sediment on any part of the transformer is more easily detected.

There are many different makes of transformer oil on the market, and there is considerable variation in their dielectric

strength and flashing point. A good oil, if thoroughly dried out, should stand from 15,000 to 20,000 volts between ball-shaped electrodes separated $\frac{1}{8}$ inch. The flashing point should not be below 130° C.; the higher it is the better, provided the oil is satisfactory in other respects.

Before an oil-filled transformer is put into use, the oil should be thoroughly dried out by heating it to about 100° C. and holding the temperature at that point until all moisture is expelled. If an iron rod heated to a point slightly below red heat causes a crackling noise, due to escaping steam, when plunged into the oil, moisture is present. The oil can be heated by a submerged electric heater.

INSULATION OF TERMINALS

55. The terminals of the coils, particularly those of the high-voltage side, must be very carefully insulated. The terminals of the high-voltage coils are connected to the line under the level of the oil. The line must be thoroughly insulated where it passes through the case, and with very high-pressure transformers precautions must be taken to prevent creepage from the line to the case. Fig. 21 shows a sectional view of an Allis-Chalmers oil-insulated water-cooled power transformer, and is typical of those used for high-pressure transmission work. Each of the high-voltage lines passes through a porcelain tube, the lower end of which dips below the oil level. This tube is slipped through a heavy porcelain insulator, which is provided with ribs to increase the leakage distance between the terminals and the cover of the transformer case.

DESIGN OF 100-KILOWATT POWER TRANSFORMER

56. To illustrate the foregoing principles, the dimensions of a power transformer will be calculated to meet the following specifications: Output, 100 kilowatts; frequency, 60 cycles; primary voltage, 10,000; secondary voltage, 2,000. Since the output is not very large, the transformer can be of

the self-cooled type, with the coils and core placed in a corrugated sheet-iron case.

57. Magnetic Flux and Density.—Fig. 20 shows that for 100 kilowatts output at 60 cycles the flux should be about 4 megalines, or 4,000,000 lines. Since the frequency is 60 cycles, the dimensions of the core will be calculated for a density of 50,000 lines per square inch.

DESIGN OF COILS

58. Primary and Secondary Turns.—Calling E_p the primary electromotive force, and T_p the number of primary turns,

$$T_p = \frac{E_p \times 10^8}{4.44\, \Phi\, n} = \frac{10{,}000 \times 10^8}{4.44 \times 4{,}000{,}000 \times 60} = 940, \text{ approximately}$$

The number of secondary turns will be 940 multiplied by the ratio of the secondary electromotive force to the primary electromotive force, or, calling the number of secondary turns T_s,

$$T_s = 940 \times \frac{2{,}000}{10{,}000} = 188$$

59. Primary and Secondary Currents.—Neglecting, for the present, the small current required to magnetize the core and supply the core losses, the primary current will be

$$I_p = \frac{\text{watts}}{\text{primary E. M. F.}} = \frac{100{,}000}{10{,}000} = 10 \text{ amperes,}$$

and the secondary current,

$$I_s = 10 \times \frac{10{,}000}{2{,}000} = 50 \text{ amperes}$$

60. Primary and Secondary Conductors.—Allowing 1,400 circular mils per ampere for the primary conductors and 1,500 for the secondary, and calling the primary current 10.75 amperes, thus making an allowance of .75 ampere for the magnetizing and iron-loss currents, the cross-section of the primary conductor should be about 1,400 × 10.75 = 15,050 circular mils; the secondary conductor should have 1,500 × 50 = 75,000 circular mils. For the primary winding, a copper

strip .4 inch wide and $\frac{1}{32}$ inch thick is suitable. This strip has a cross-section of $400 \times 31.25 = 12{,}500$ square mils, which equals, when the corners are rounded, 15,000 circular mils. This strip will be wound flat, thus making a thin pancake coil with one turn per layer. The cotton insulation on the strip will add about 12 mils to its breadth, and the stay binding around the coil will further increase the breadth. Allowing a slight amount also for irregularities in the surface of the coil, it will be safe to take the total breadth occupied in the transformer as $\frac{1}{2}$ inch.

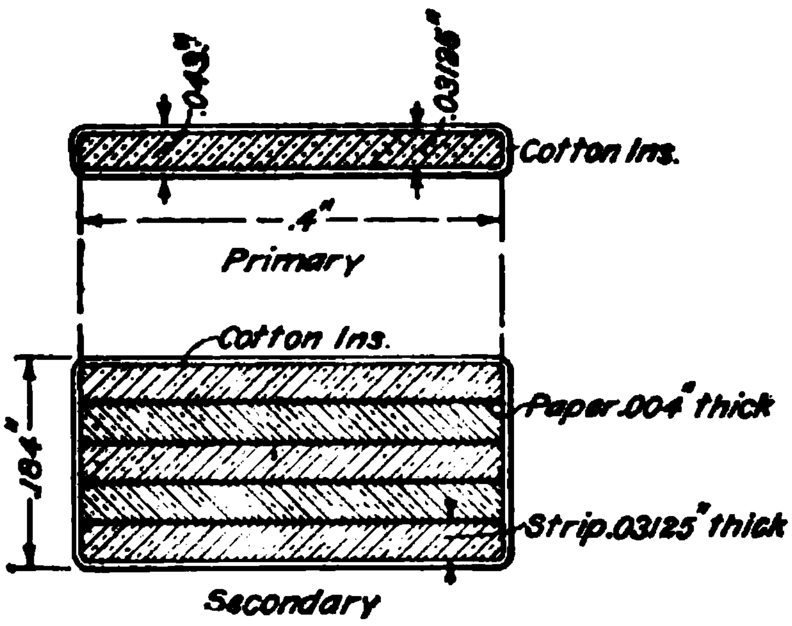


Fig. 22

The secondary conductor may consist of bare copper strip of the same size as the primary ($.4 \times \frac{1}{32}$), but with five strips in parallel, thereby obtaining a cross-section of 75,000 circular mils. Thin bond paper (.004 inch thick) will be placed between layers to prevent eddy currents, and the conductor as a whole will be wrapped with double cotton covering. The complete conductor will contain five strips of copper, each $\frac{1}{32}$ inch thick, four strips of .004-inch insulation, and an outside wrapping of double cotton, making the total thickness .184 in. Fig. 22 shows sections of the primary and secondary conductors.

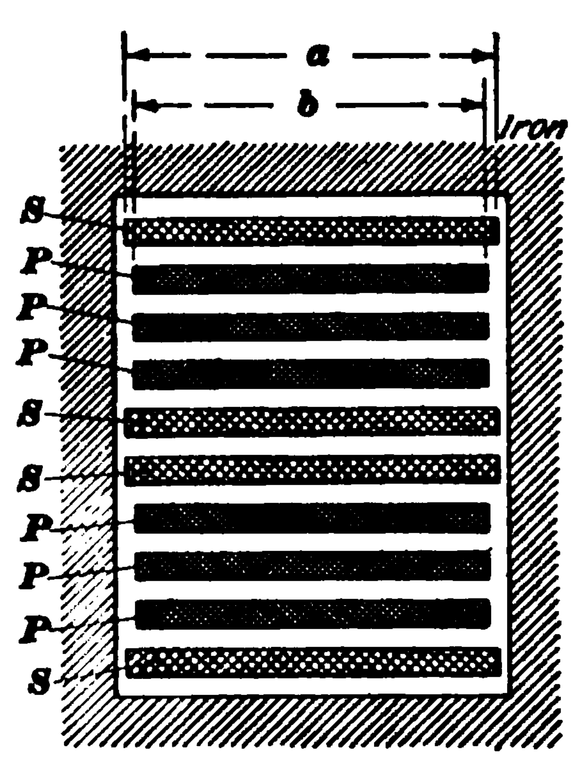


Fig. 23

61. Arrangement of Coils. There are 940 turns in the primary and 188 in the secondary. The coils will be arranged in six primary and four secondary sections, as shown in Fig. 23.

The primary sections will average $940 \div 6 = 156\frac{2}{3}$ turns each, and in order to make a whole number of turns per coil, four of the coils can be made with 157 turns each and the other two with 156 turns each. The conductor is .043 inch thick over the insulation, and allowing 12 mils for pressboard or other insulation wound between turns, the total thickness per turn will be $.043 + .012 = .055$ inch. The total breadth of winding in the primary is, therefore, $.055 \times 157 = 8.64$, say $8\frac{5}{8}$, inches over the outside taping.

The secondary winding is divided into four sections; hence, the number of turns per section is $188 \div 4 = 47$. The conductor is .184 inch thick over insulation, and allowing 12 mils additional for the insulating strip between the turns of the coil, the total thickness per turn is $.184 + .012 = .196$ inch. This makes the total thickness of the secondary winding $47 \times .196 = 9.21$, say $9\frac{1}{4}$, inches. The arrangement of the iron core around the coils will be as shown in Fig. 14, the core being built up of strips overlapped at the corners. Fig. 24 shows a section through the coils in one of the openings.

CORE DIMENSIONS

62. Since the dimensions of the coils have been fixed, the space that they will occupy can be determined. Fig. 24 shows the dimensions and arrangement of the coils in one half of the transformer, the primary, or high-voltage, coils being marked *P* and the secondary, or low-voltage, coils *S*. A $\frac{1}{4}$-inch space is left between each two adjacent sections. As large a space as this is hardly necessary to insulate for 10,000 volts, but if the space is made much smaller, the oil circulation through the ducts between the coils will be impeded. Around the assembled coils will be placed a wrapping of four layers of fullers' board, each layer .01 inch thick. Between the primary sections and between primary and secondary will be placed diaphragms of four thicknesses of .01-inch fullers' board, and around the groups of primary coils will be wrapped four thicknesses of .01-inch fullers' board, thus making eight thicknesses of fullers'

board between primary and secondary sections. The coils will be held apart by hardwood strips, and similar strips will be placed outside the coils to keep them spaced correctly with regard to the iron. With ¼-inch spacing between coils and ¼-inch spacing all around the sides, the dimensions of the opening through the core will be 10¼ in. × 10¼ in.

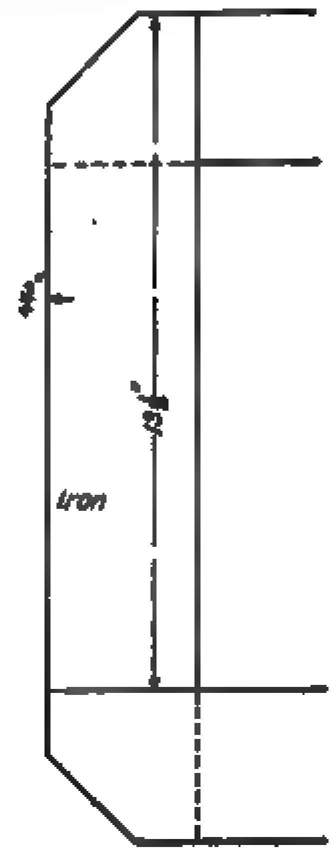


FIG. 24

63. Dimensions of Core Punchings.—The *core tongue*, or that part passing through the center of the coils, must have enough cross-sectional area to carry the flux without exceeding the assumed density of 50,000 lines per square inch; that is, the cross-section must be 4,000,000 ÷ 50,000 = 80 square inches, net. If only 90 per cent. of the gross sectional area is iron, the gross area must be 80 ÷ .9 = 89 square inches. Since half the flux is carried by each of the two cores, each core must have $\frac{89}{2} = 44\frac{1}{2}$ square inches cross-section. If the core punchings are very narrow, the core must be built higher in order to obtain the required cross-section; this makes the mean length of a turn in the coils long and increases the copper loss. On the other hand, if

the strips are very wide, the breadth of the transformer is increased, and this also increases the length of the mean turn. Moreover, if the core is made very wide, the iron is not as readily cooled. For a transformer of this output, 3 inches will be a fair value for the width of the strips, and the height of the core, measured perpendicularly to the paper in Fig. 24, will be $44.5 \div 3 = 14.83$, say $14\frac{7}{8}$, inches.

The core strips will be $13\frac{1}{2}$ in. $\times$ 3 in. and $13\frac{1}{4}$ in. $\times$ 3 in., as shown in Fig. 24. The corners will be chamfered, to give the same cross-section in them as in the remainder of the core, and a space of $\frac{3}{4}$ inch will be allowed between the two cores where they pass through the opening in the coils.

LOSSES

64. The **losses** in a transformer are calculated in exactly the same way as explained for alternators and induction motors. The copper loss is found by first measuring off the mean length of a turn as obtained from a drawing of the coils. The resistance is then readily calculated from the known number of turns and the cross-section of conductor. The primary and secondary I^2R losses are then calculated separately, and the two added together to give the total copper loss.

The core volume is estimated from the drawings, and the loss per cubic inch is obtained from the curve given in *Design of Alternating-Current Apparatus*, Part 1, for iron loss in transformers. It will not be necessary to go through the calculations in detail, as they would be similar to those previously made for the design of the alternator and the induction motor.

65. ***I^2R* Loss.**—The mean length of a turn in primary and secondary coils is approximately 80 inches; cross-section of the primary conductor, 15,000 circular mils; number of turns, 940; hot resistance of primary, 5 ohms; primary current at full load, about 10.75 amperes; primary I^2R loss at full load, 580 watts, approximately; secondary current at full

load, 50 amperes; cross-section of secondary conductor, 75,000 circular mils; number of turns, 188; secondary resistance, .2 ohm; secondary I^2R loss at full load, 500 watts; and total I^2R loss, 580 + 500 = 1,080 watts.

66. Core Loss.—The net volume of iron in core is 4,150 cubic inches, approximately; density in core, 50,000 lines per square inch; loss per cubic inch, as obtained from the curve previously given, .4 watt, and total core loss, 1,660 watts. The copper loss is about 65 per cent. of the iron loss—a good proportion for a power transformer where the load is steady and close regulation desired.

EFFICIENCY

67. The **efficiency** of the transformer at different loads is readily obtained from the I^2R and core loss just calculated.

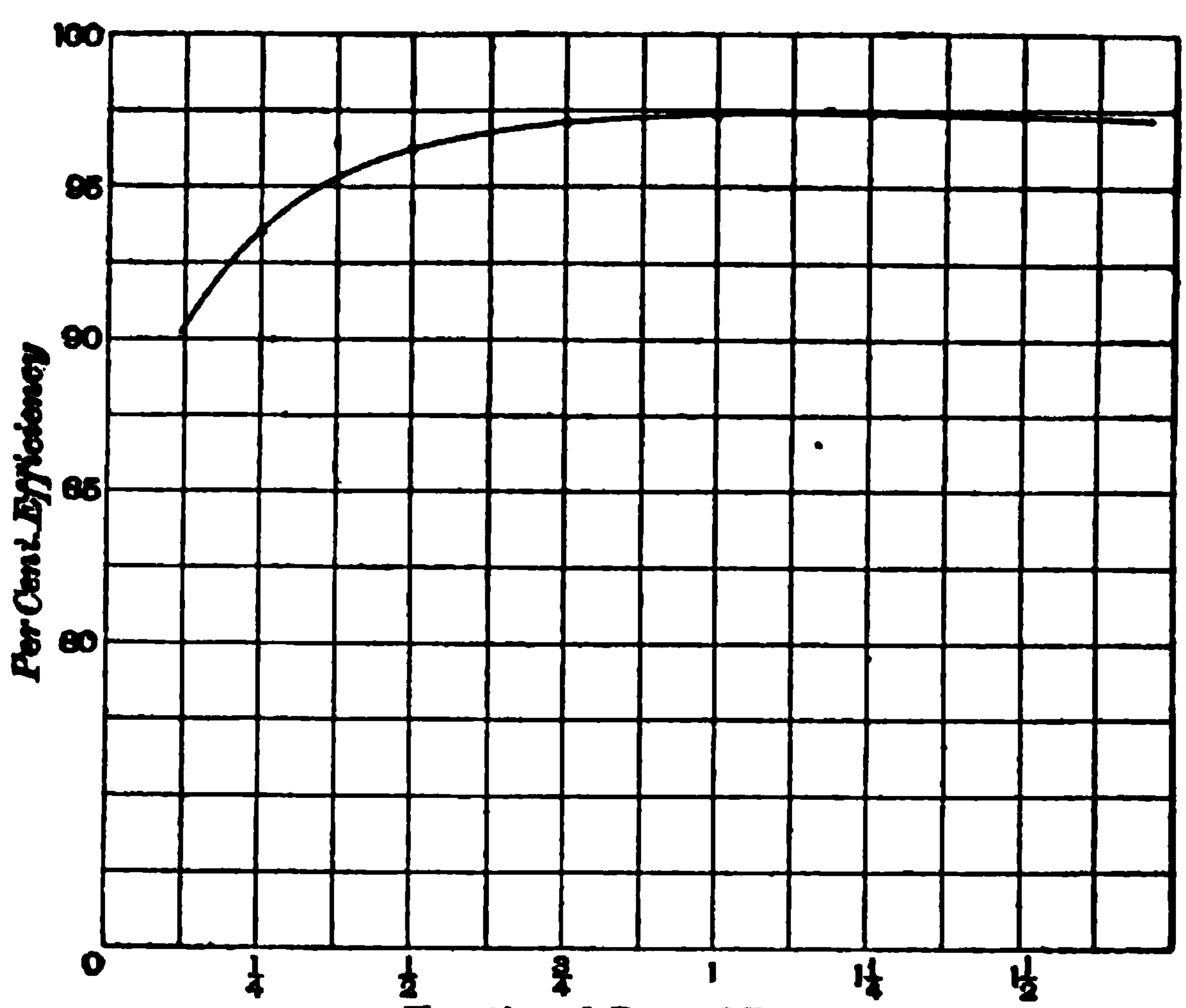


FIG. 25

The core loss remains practically constant at all loads, while the copper loss varies as the square of the load. Table I shows the losses and efficiencies at various loads.

In Fig. 25, the efficiencies are plotted in the form of a curve, of which the upper part only is shown. The efficiency

TABLE I

TRANSFORMER EFFICIENCY

Proportion of Load	I^2R Loss Watts	Core Loss Watts	Total Loss Watts	Output Watts	Input Watts	Efficiency Per Cent.
$\frac{1}{4}$	67	1,660	1,727	25,000	26,727	93.54
$\frac{1}{2}$	270	1,660	1,930	50,000	51,930	96.26
$\frac{3}{4}$	607	1,660	2,267	75,000	77,267	97.07
1	1,080	1,660	2,740	100,000	102,740	97.33
$1\frac{1}{4}$	1,690	1,660	3,350	125,000	128,350	97.39
$1\frac{1}{2}$	2,430	1,660	4,090	150,000	154,090	97.35

rises very rapidly between zero and one-half load and is nearly constant between one-half load and 50 per cent. overload.

NO-LOAD CURRENT

68. The current taken from the line at full voltage and with the secondary on open circuit is commonly called the *magnetizing current* of the transformer. Strictly speaking, the true magnetizing current is the component of the no-load current that sets up the magnetic flux; this, combined with the watt component necessary to supply the core loss, gives the actual no-load current. The magnetizing and watt components are at right angles to each other, and

$$\text{no-load current} = \sqrt{(\text{magnetizing current})^2 + (\text{loss current})^2}$$

69. Loss Current.—There is a small I^2R loss in the primary due to the no-load current, but it is so small that it can be neglected without appreciable error. The loss component of the no-load current will therefore be that required for the core loss of 1,660 watts; with a primary pressure of 10,000 volts, this is equivalent to $1,660 \div 10,000 = .166$ ampere.

70. Magnetizing Current.—The primary coil must furnish enough ampere-turns to set up the magnetic flux through a path of average length, as indicated by the dot-and-dash line, Fig. 24. The length of path is approximately 51 inches, and, for a density of 50,000 lines per square inch, about 14 ampere-turns per inch length of path is required, as shown by the magnetization curve previously given. This calls for $51 \times 14 = 714$, say 800, ampere-turns, in order to make some allowance for reluctance of joints. Since the primary has 940 turns, the current is $800 \div 940 = .85$ ampere, approximately.

The no-load current is the diagonal of the parallelogram having sides .166 and .85 at right angles to each other, or

$$\text{no-load current} = \sqrt{(.85)^2 + (.166)^2} = .87 \text{ ampere, nearly}$$

This is not far from the allowance of .75 ampere made at the outset of the design; the general design would not be affected by the slight difference.

POLYPHASE TRANSFORMERS

71. Transformers for two- or three-phase currents can be made by combining two or three single-phase trans-

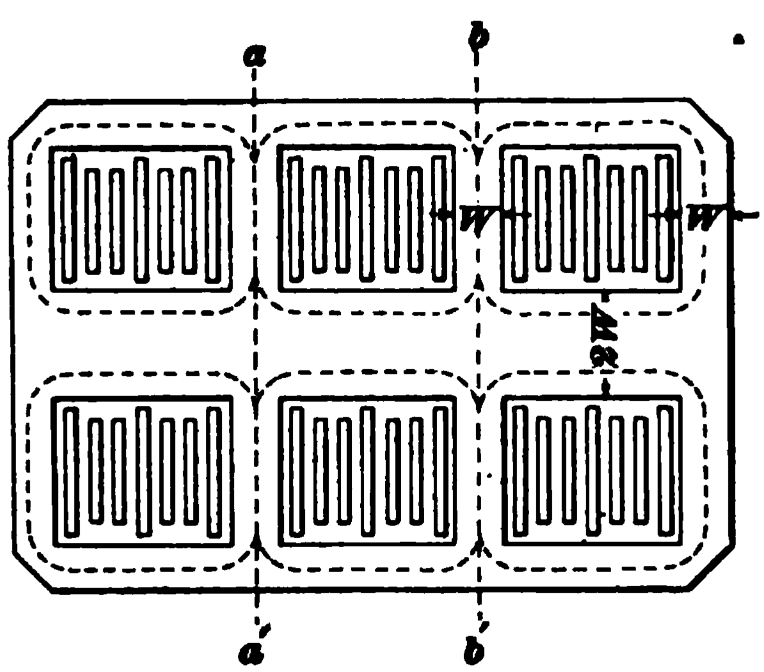


FIG. 26

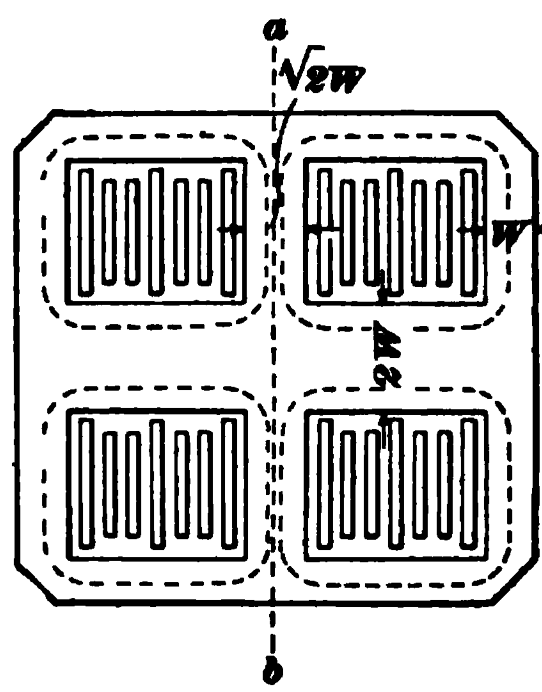


FIG. 27

formers into one piece of apparatus. The general practice is to employ two or three separate single-phase transformers for transforming polyphase currents, but in some

cases **polyphase transformers** are desirable. Figs. 26 and 27 show the usual arrangement of coils and core for shell-type polyphase transformers. In the three-phase type shown in Fig. 26, the device is equivalent to three single-phase transformers placed against one another along lines $a\,a'$ and $b\,b'$. There are three distinct sets of coils, but the core forms a part common to all three. By thus combining the core, a certain saving of iron is effected and the core loss reduced slightly; in addition to this, the floor space occupied by the transformer is decreased. For example, along the lines $a\,a'$ and $b\,b'$ where the cores join, the width of iron W can be made equal to the width outside the coils. If separate single-phase transformers were used, the width would be the same on all four sides of a coil, thus making the part between the transformers 2 W. The flux in the iron along lines $a\,a'$ and $b\,b'$ is the resultant of two fluxes differing in phase by 120°; hence, the sum of the two is the same as the single flux, and a width of iron W is sufficient to carry it.

If a three-phase transformer is used instead of three separate single-phase ones, each in its own case, the saving in floor space may amount to about 30 per cent., but if the comparison is made between a three-phase transformer and three single-phase ones mounted in the same case, the saving in floor space becomes very small.

A two-phase transformer, Fig. 27, effects but little saving over two single-phase ones. Since the flux is the resultant of two fluxes at 90° instead of 120°, the width of iron along line $a\,b$ must be $\sqrt{2}\,W$.

In the design of polyphase transformers, the calculations of coils and core are made exactly the same as for single-phase transformers, with the exception of the differences in thickness of iron between the coils as just explained. Each set of windings is treated as a single-phase element.

AUTOTRANSFORMERS

72. Autotransformers differ from the ordinary kind, in that they transform only part of the total power supplied them, and also in having the primary and secondary coils connected in series, instead of being entirely separate. In a regular transformer, the two coils have no electrical connection with each other, and, neglecting losses, the whole of the power supplied to the primary is transferred to the secondary through the medium of the alternating magnetic field. In an autotransformer, part of the power is transferred by direct electrical conduction from primary to secondary, and part through the medium of the alternating flux.

In Fig. 28 (*a*) is shown a diagram of the winding of an

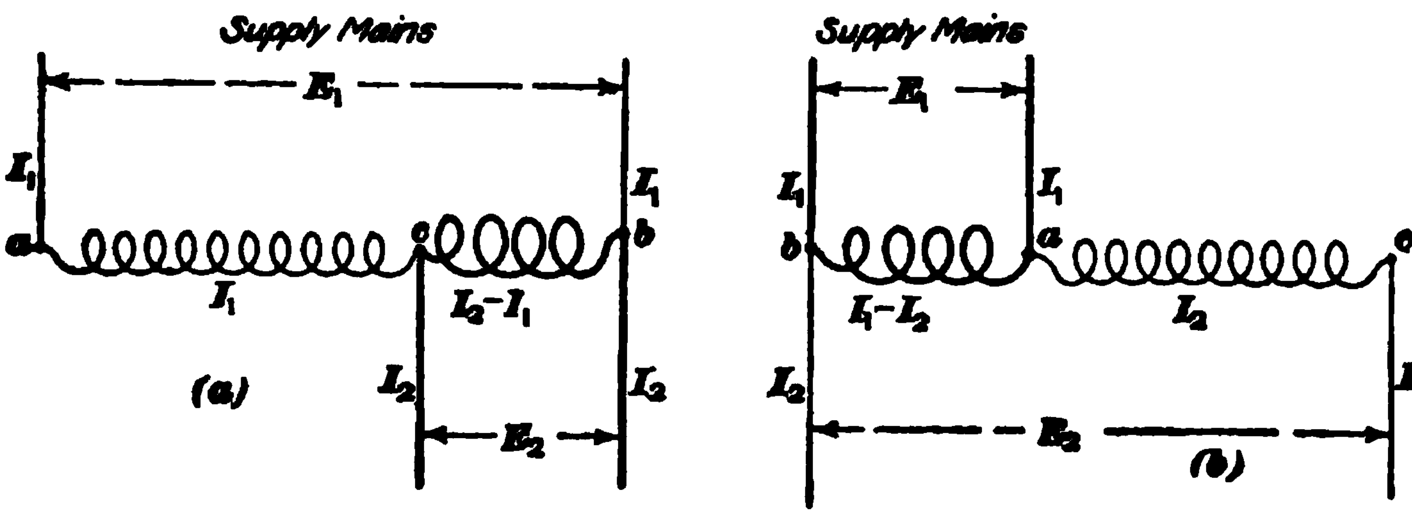


FIG. 28

autotransformer arranged to step the voltage down, and in (*b*) is shown a diagram of one for stepping the voltage up. In (*a*) the high-voltage mains are the primary, while in (*b*) the high-voltage mains are the secondary. In both cases, the primary voltage is designated by E_1, the primary current by I_1, and the secondary voltage and current by E_2 and I_2, respectively. Also, in both cases, the winding is represented as being made of two coils, one of fine wire and the other of coarse wire. This may or may not be the case, according to the service the transformer is to perform and according to the ratio of transformation. That portion of the transformer winding between points *a* and *b* to which the primary, or supply, mains are connected may be considered as the primary winding, and that portion between points *b* and *c* to which

the secondary mains are connected, the secondary winding. In (*a*), both coils in series constitute the primary winding, and the coarse-wire, or low-voltage, coil is the secondary winding; in (*b*), the coarse-wire, or low-voltage, coil is the primary, and both coils in series form the secondary.

73. Whatever may be the arrangement of the primary and secondary windings, the law of transformation of pressures is the same as for transformers having two coils insulated from each other; that is, if T_1 is the number of turns in the primary winding and T_2 the number in the secondary,

$$\frac{E_1}{E_2} = \frac{T_1}{T_2}$$

Neglecting losses, the primary input and the secondary output are equal; that is,

$$E_1 I_1 = E_2 I_2$$

or,

$$\frac{E_1}{E_2} = \frac{I_2}{I_1} = \frac{T_1}{T_2}$$

$$I_2 = \frac{T_1}{T_2} I_1$$

In other words, the current in the secondary equals that in the primary multiplied by the ratio between the number of primary turns and the number of secondary turns.

Referring to Fig. 28 (*a*), the current in the transformer winding between the points *a* and *c* is I_1; but the current in the secondary winding between *b* and *c* is $I_2 - I_1$, because the current in the secondary winding of a transformer always flows in a direction to oppose the magnetizing effect of the current in the primary. In (*b*), the current in the portion of the winding between points *c* and *a* is I_2, and between points *b* and *a*, that is, in the primary, is $I_1 - I_2$.

The power actually transformed is the product of the secondary-coil current and the induced electromotive force, or, for a step-down transformer, Fig. 28 (*a*), $E_2(I_2 - I_1) = E_2 I_2 - E_2 I_1$. $E_2 I_2 = E_1 I_1$; hence,

$$\text{power transformed} = E_1 I_1 - E_2 I_1 = I_1 (E_1 - E_2) \qquad (1)$$

By a similar process for step-up autotransformers, Fig. 28 (*b*),

$$\text{power transformed} = I_2(E_2 - E_1) \qquad (2)$$

In (*a*), the high-voltage current is I_1, while in (*b*), it is I_2, so that the following rule applies to autotransformers, whether used to raise or lower the voltage:

Rule.—*In an autotransformer, the power transformed is equal to the current taken from the high-voltage terminals multiplied by the difference between the two voltages.*

For example, an autotransformer steps down from 2,000 to 1,000 volts and supplies a secondary current of 50 amperes. Neglecting losses, the input and the output are each 50 kilowatts, and the primary current is 25 amperes. The power transformed is $I_1(E_1 - E_2) = 25 \times (2{,}000 - 1{,}000) = 25{,}000$ watts, or 25 kilowatts, that is, one-half the input. If a regular transformer with two coils insulated from each other were used, it would have to be capable of transforming the whole input, or 50 kilowatts. In this case, therefore, the autotransformer would be half as large as the regular transformer and would cost considerably less.

74. In formula **1**, Art. **73**, if the low voltage E_2 is one-half the high voltage E_1, the power transformed is $\frac{I_1 E_1}{2}$, that is, one-half the input, as just shown numerically. If $E_2 = \frac{E_1}{3}$, the power transformed is $\frac{2 E_1 I_1}{3}$, or two-thirds the input, and the autotransformer would have to be two-thirds as large as a regular transformer for the same output. The comparative sizes of the two kinds of transformers are thus seen to depend on the ratio of transformation. Where the ratio of transformation is low (primary and secondary voltage not differing greatly), there is considerable gain by using an autotransformer, but where the voltages differ widely there is little gain over an ordinary transformer.

The use of autotransformers is confined chiefly to places where there is no objection to having the two coils in electrical

connection, and usually to places where the two voltages do not differ widely; as, for supplying voltmeters on moderately low-voltage switchboards, for starting induction motors, synchronous motors, and rotary converters, for regulating the voltage applied to single-phase alternating-current railway motors, for regulating the line voltage on alternating-current lighting systems, etc. For many of these uses, autotransformers are known as *compensators*. For general lighting and power service, autotransformers cannot be used, because they connect the high-tension primary to the low-tension secondary, thus making the secondary dangerous to life and property.

ROTARY CONVERTERS

75. The design of **rotary converters,** or **rotary transformers,** is largely a matter of direct-current dynamo design. However, on account of the peculiar way in which these machines are used, their design is limited by some considerations that do not apply to regular direct-current generators. When operated in the ordinary way, a rotary converter is supplied with alternating current and delivers direct current; the machine operates as a synchronous motor, and at the same time acts as a direct-current generator. As shown later, it is difficult to meet both of these requirements for all frequencies and direct-current voltages.

76. Number of Poles and Speed.—Before beginning the design of a rotary converter, the frequency of the supply current and the voltage and output of direct current must be known. If n is the frequency, p the number of poles, and s the revolutions per second,

$$n = \frac{p}{2}s, \text{ or } s = \frac{2n}{p}$$

That is, with a given number of poles and a given frequency, the speed is fixed, and the number of poles must be selected so that the direct-current voltage and output will be correct and the general performance as a direct-current generator satisfactory. The number of speeds available is

therefore limited, as compared with regular direct-current generators.

77. Frequency and Voltage.—Rotary converters are usually made for direct-current pressures of 600 volts or lower, and for frequencies ranging from 60 to 25 cycles. It is difficult to make good machines for both high frequency and high voltage. High frequency necessitates a large number of poles to keep the speed within safe limits, and high voltage necessitates a large number of commutator bars per pole to keep the volts per bar within safe limits. High-frequency high-voltage converters, therefore, must have a very large number of commutator bars, necessitating a commutator of large diameter. This leads to high commutator peripheral speed, and makes it difficult to keep the brushes and commutator surface in good condition. In order not to make the peripheral speed of the commutator too high, it is necessary to keep the volts between bars high and the brushes close together. With the suddenly fluctuating loads of street-railway service, such machines are liable to flash over at the commutator.

The relation between the peripheral speed V of the commutator, the distance d, in inches, along the commutator surface between brushes, and the frequency n may be shown in the following manner. Since $n = \frac{p}{2} \times s$ and $s = \frac{\text{R. P. M.}}{60}$

$$n = \frac{p \times \text{R. P. M.}}{120}, \text{ or } p \times \text{R. P. M.} = 120n$$

The circumference of the commutator, in feet, is $\frac{d}{12} \times p$, and

$$V = \frac{d}{12} \times p \times \text{R. P. M.} = \frac{d}{12} \times 120n = 10dn$$

If the peripheral velocity V is too high, the brushes will chatter and spark. The highest practical limit with carbon brushes is about 4,500 feet per minute. If $V = 4{,}500$ and $n = 60$,

$$d = \frac{4{,}500}{10 \times 60} = 7.5 \text{ inches}$$

This is a very short distance to separate the brushes on a high-voltage machine, especially one used for railway work. With low voltage, the space between brushes can be reduced, as it is not necessary to have so many armature turns and commutator bars per pole; this permits a lower peripheral speed on the commutator and gives a machine that will operate without any trouble.

78. In many cases, it is on account of the limitations just mentioned that motor-generator sets are used in preference to rotary converters for converting from 60-cycle alternating current to 500- to 600-volt direct current. With 25 cycles, there is no difficulty in making thoroughly satisfactory converters for 600 volts. If the load is comparatively steady, 600-volt 60-cycle converters may operate quite well, but with the violently fluctuating loads found on small railway systems, such converters are not so reliable as motor-generator sets.

ELECTRIC TRANSMISSION

INTRODUCTORY

1. Electric transmission may be defined as the transferring of power from one point to another by means of electricity. The power so transmitted may be used for any of the numerous applications to which electricity is now adapted, such as operating motors, lights, electrolytic plants, etc. The distance over which the power is transmitted may vary from a few feet, as in factories, to many miles, as in some of the modern long-distance transmission plants.

2. A power-transmission system consists of three essential parts: (*a*) The station containing the necessary dynamos and prime movers for generating the electricity; (*b*) the line for carrying the current to the distant point; and (*c*) the various receiving devices by means of which the power is utilized.

3. Electric transmission may be carried out by using direct current, alternating current, or a combination of the two. Generally speaking, in cases where the transmission is short, direct current is used, though alternating current is now also largely used for short-distance transmission, as, for example, in driving factories. When the distance is long, it is necessary to use alternating current. In cases where the distance is long and where alternating current is not well adapted to the operation of the receiving devices, the current transmitted over the line is alternating, but it is changed to direct current at the distant end and there distributed, thus forming a combination of the two systems. The special applications of electric transmission to railway

and lighting work will be taken up later in connection with those branches of the subject; for the present, the object is only to bring out important points relating to the subject of electric-power transmission generally.

Power transmission is extensively used in connection with water powers that would in many cases be of little use on account of their being located away from railways or commercial centers. It is also coming into extensive use in factories to replace long lines of shafting and numerous belts, which are wasteful of power. Its most important use, however, is in connection with the operation of electric railways, where the power is transmitted from the central station to the cars scattered over the line. The style of apparatus used will depend altogether on the special kind of work that the plant is to do, and the type best adapted for a given service will be described when the different transmission systems are treated later. Power stations will be taken up by themselves; the present Section will be confined to the methods and appliances used for carrying out electrical transmission.

POWER TRANSMISSION BY DIRECT CURRENT

4. Up to within a comparatively recent date, electric transmission for power purposes was carried out by means of the **direct current,** alternating current being used when the power was required for lighting purposes only. Later, however, alternating-current motors and rotary converters came into use, and at the present time, large transmission systems use alternating current for both light and power.

5. Dynamos and Motors Used.—Direct-current dynamos may be of either the constant-current or the constant-potential type. Practically all the current is distributed at constant potential and in America compound-wound dynamos are generally used. The motors used in connection with such constant-potential systems are generally of the shunt or compound type.

6. Simple Power-Transmission System.—About the simplest possible example of electric-power transmission is that shown in Fig. 1. Here a compound-wound dynamo *A* is driven by means of an engine not shown, and sends current through the motor *B* by means of the lines *M*, *M*. The dynamo is driven at constant speed and its series-winding is adjusted so that the pressure at the terminals of the dynamo rises slightly as the current increases, due to the increase of the load on the motor. This slight rise in voltage is to make up for the loss in pressure in the line, as will be explained later. The pressure at the motor remains nearly constant, no matter what load the motor may be carrying, but the current supplied increases as the load is increased. When

FIG. 1

both lights and motors are operated, such a system will probably use a pressure of 110 or 220 volts at the receiving

end of the circuit; if used for power alone, a pressure of 250 or 500 volts will be employed. It should be mentioned that when the **receiving** end of a circuit is spoken of, the end distant from the station is meant, because this is the end where the various devices, such as lamps, motors, etc., receive their current.

7. Lost Power and Line Drop.—In order that a transmission plant may be efficient, the generating apparatus, line, and motors must be efficient. Dynamos and motors of good make are generally satisfactory as regards efficiency, and the question is, How efficient can the line be made? In answer to this, it might be said that the loss of power in the line could be made as small as we please if expense were no consideration. All conductors, no matter how large, offer some resistance to the current and there is bound to be some loss in power. By making the conductor very large we can make the loss small, because the resistance will be low, but a point is soon reached where it pays better to allow a certain amount of power to be lost rather than to further increase the size of the conductor. The pressure necessary to force the current over the line is spoken of, in power-transmission work, as the **drop** in the line, because this pressure is represented by a falling off in voltage between the dynamo and the distant end of the line.

8. If R is the resistance of the line and I the current flowing, the drop is, from Ohm's law, $e = IR$. The power, in watts, lost in the line is $IR \times I = I^2 R = W$. The power lost, due to the resistance encountered by the current, reappears in the form of heat. The power generated by the dynamo is equal to the product of the pressure generated by the dynamo and the current flowing; or, if E_1 represents the dynamo pressure, then

$$\text{watts generated} = W_1 = E_1 I \qquad (1)$$

The power delivered at the end of the line is equal to the product of the pressure at the end of the line multiplied by

the current, or, if E_2 represents the pressure at the distant, or receiving, end, then

$$\text{watts delivered} = W_2 = E_2 I \qquad (2)$$

It should be particularly noted at this point that the current I is the same in all parts of the circuit. Thus, in Fig. 1 the same current flows through the motor that flows through the dynamo, unless there is a leakage at some point between the lines, and this would not be the case if the lines were properly insulated. What does occur is a drop or loss in pressure between the station and the receiving end, but there is practically no loss in current except, perhaps, in a few cases where the line pressure is exceedingly high or the insulation unusually bad. This point is mentioned here because the mistaken idea that there is a loss of current in the line is a common one.

9. We have already seen that the number of watts lost in the line is given by the equation $W = I^2 R$.

The lost power must also be equal to the difference between the power supplied and the power delivered, or $W = W_1 - W_2, = E_1 I - E_2 I, = I(E_1 - E_2)$.

$E_1 - E_2$ represents the loss of pressure, or the drop, and it is at once seen that the greater the drop, the greater the loss in power. For example, a 5-per-cent. drop in voltage is equivalent to a 5-per-cent. loss of power in the line.

10. In order to transmit power, we must be willing, then, to put up with a certain amount of loss, or what is equivalent, with a certain amount of drop in the line. The amount of drop can be made anything we please, depending on the amount of copper we are willing to put into the line. The percentage of drop allowed is seldom lower than 5 per cent. and not often over 15 per cent. except on very long transmission lines; 10 per cent. is a fair average. In cases where the distribution is local, as, for example, in house wiring, the allowable drop from the point where the current enters the building to the farthest point on the system may be as low

as 1 or 2 per cent. If the drop is excessive, the pressure at the end of the line is apt to fluctuate greatly with changes of load and thus render the service bad. In a few special cases there may be conditions that warrant the use of an excessive drop, but in general the above values are the ones commonly met with.

11. When the loss, or drop, in a circuit is given as a percentage, this percentage may refer either to the voltage at the station end of the line, or the voltage at the receiving end. For example, suppose we take the case where the percentage loss refers to the voltage at the station end, and let

E_1 = voltage at dynamo;
E_2 = voltage at end of line;
$\%$ = percentage loss (expressed as a number, not as a decimal);
e = actual number of volts drop in the line.

Then, $$E_1 = \frac{100\,E_2}{100 - \%} \qquad (3)$$

And $$e = \frac{100\,E_2}{100 - \%} - E_2 \qquad (4)$$

EXAMPLE.—The voltage at the end of a lighting circuit is to be 110 and the allowable drop is to be 3 per cent. of the dynamo voltage. (*a*) What will be the dynamo voltage? (*b*) What will be the actual drop, in volts, in the circuit?

SOLUTION.—(*a*) We have $E_1 = \frac{100 \times 110}{100 - 3} = 113.4$. Ans.

(*b*) The drop $e = \frac{100 \times 110}{100 - 3} - 110 = 3.4$ volts. Ans.

12. It is frequently more convenient to express the loss as a percentage of the power delivered at the end of the line. For example, if the voltage at the end of the line were 110, and the loss were to be an amount equivalent to 3 per cent. of the power delivered, instead of 3 per cent. of the power generated, it would mean that the allowable drop was 3 per cent. of 110, or 3.3 volts, instead of 3.4 volts. Railway generators are commonly spoken of as being adjusted for

10 per cent. loss when they are wound so as to generate 500 volts at no load and 550 volts at full load; i. e., 50 volts, or 10 per cent. of 500, is allowed as drop in the line, 500 being the voltage at the end of the line. In expressing the loss as a percentage, then, it should be distinctly understood as to whether this percentage refers to the power generated or the power delivered, otherwise there is liable to be confusion. The best way is to express the drop directly in volts and then there can be no doubt as to what is meant. In what follows, we will, when expressing the loss as a percentage, refer to the power delivered unless it is otherwise specified, as this method is now very generally followed.

LINE CALCULATIONS

13. Calculations for Two-Wire System.—We are now in a position to look into the method of determining the size of wire necessary for a given case. First consider the simple transmission system, shown in Fig. 1. The problem of determining the size of a line wire usually comes up about as follows: Given a certain amount of power to be transmitted over a given distance with a given amount of loss; also, given the required terminal voltage; determine the size of line wire required. The whole problem of determining the size of line wire simply amounts to estimating the size of wire to give such a resistance that the drop will not exceed the specified amount. All the formulas for this purpose are based on Ohm's law, and are simply this law arranged in a more convenient form to use. There have been a large number of these formulas devised, each for its own special line of work, and the one that is derived below is given because it is as generally applicable as any.

14. In the first place, if the watts or horsepower to be delivered and the voltage at the end of the line are given, we can at once determine the current, because

$$I = \frac{W_s}{E_s} \qquad (5)$$

in which W_s is the power delivered. Furthermore, the drop e in the line is known or specified, and since

$$e = IR \qquad (6)$$

or $R = \frac{e}{I}$, the resistance R of the line is easily determined.

15. Referring to Fig. 1, it is seen that the total length L of line through which the current flows is twice the distance from the dynamo to the end of the line. It has already been shown that the resistance of a wire is directly proportional to its length and inversely proportional to the area of its cross-section, or $R = \frac{KL}{A}$, where K is a constant that depends on the units used for expressing the length L and the area of cross-section A. In practice, it is generally most convenient to have the length L expressed in feet and the area A in circular mils. When these units are used, the quantity K is the resistance of 1 **mil-foot** of wire; i. e., the resistance of 1 foot of wire $\frac{1}{1000}$ inch in diameter. If the area of cross-section of the wire were only 1 circular mil, it is evident that the resistance of L feet of it would be KL, and if the area of the wire were A circular mils, its resistance would be $\frac{KL}{A}$.

The resistance of 1 mil-foot of copper wire, such as is used for line work, may be taken as 10.8 ohms. This resistance will, of course, vary with the temperature and also with the quality of the wire used, but the above value is close enough for ordinary line calculations. The following formula may then be used for calculating the resistance of any line:

$$R = \frac{10.8\,L}{A} \qquad (7)$$

where R = resistance in ohms;
L = length of line in feet (total length, both ways);
A = area of cross-section in circular mils.

16. What is usually desired is the area of the wire required for the transmission, not the resistance, and by combining formulas **6** and **7** this can be obtained.

We have $$e = IR,$$

but $$R = \frac{10.8\,L}{A};$$

hence, $$e = \frac{10.8\,L\,I}{A},$$

or $$A = \frac{10.8\,L\,I}{e} \qquad (8)$$

Expressing this formula in words, the required area of cross-section in circular mils

$$= \frac{10.8 \times \text{length of line in feet} \times \text{current in amperes}}{\text{drop in volts}}$$

This rule for determining the size of wire for a given transmission may be written as follows:

Rule.—*Take the continued product of 10.8, the total length of the line in feet, and the current in amperes; divide by the drop in volts, and the result will be the area of cross-section in circular mils.*

17. It will be noticed that the size of wire has been determined by making it of such dimensions that the drop will not exceed the allowable amount. In other words, the drop has been made the determining factor and no attention has been paid to the current-carrying capacity of the wire. If the distance were very short and the drop allowed were large, the size of the wire as given by the formula might be such that it would not carry the current without greatly overheating. This is an important consideration where wires are run indoors, because the distances are then short and the rise in temperature of the wire needs to be carefully considered, owing to the fire risk. This point will be taken up in connection with interior wiring. For line work such as we are now considering, the distances are usually so long that the size of wire as determined by the allowable drop is nearly always much larger than would be necessary to carry the current without overheating.

18. The formula just given is also often written in the form

$$A = \frac{21.6\,D\,I}{e} \qquad (9)$$

where D is the distance (one way) from the station to the center where the power is delivered. Evidently, D is only one-half the length of wire through which the current flows; i. e., $L = 2\,D$; hence the constant 21.6 is used instead of 10.8.

19. Formulas **8** and **9** may be applied to a large number of cases if care is taken to see that the proper values are substituted. The length L or distance D must always be expressed in feet. The use of the formulas will be illustrated in connection with the following examples. Table I, giving the area in circular mils of the various sizes of wire according to the Brown & Sharpe gauge, is here inserted for convenient reference in connection with the examples.

TABLE I

SECTIONAL AREA OF B. & S. WIRES

No. B. & S.	Cross-Section Circular Mils	No. B. & S.	Cross-Section Circular Mils	No. B. & S.	Cross-Section Circular Mils
0000	211,600	11	8,234	25	320
000	167,805	12	6,530	26	254
00	133,079	13	5,178	27	202
0	105,535	14	4,107	28	160
1	83,694	15	3,257	29	127
2	66,373	16	2,583	30	101
3	52,634	17	2,048	31	79.7
4	41,742	18	1,624	32	63.2
5	33,102	19	1,288	33	50.1
6	26,251	20	1,022	34	39.7
7	20,816	21	810	35	31.5
8	16,509	22	642	36	25.0
9	13,094	23	509	37	19.8
10	10,381	24	404	38	15.7

EXAMPLE 1.—In Fig. 1 the pressure at the receiving end of the line is to be 500 volts, and 40 kilowatts is to be transmitted with a drop of 50 volts. The distance from the station to the end of the line is 3 miles. Calculate the cross-section of wire necessary and give the nearest size B. & S. that will answer.

SOLUTION.— 40 K. W. = 40,000 watts; hence, current $= \frac{40000}{500}$ = 80 amperes. The distance from the station to the end of the line is 3 mi., but the current has to flow to the end and back again, so that the length of line L through which the current flows is 6 mi., or 31,680 ft. Applying formula **8**,

$$A = \frac{10.8 \times 31{,}680 \times 80}{50} = 547{,}430 \text{ circular mils, nearly. Ans.}$$

This is considerably larger than any of the B. & S. sizes, so that a stranded cable would be used.

FIG. 2

EXAMPLE 2.—It is desired to transmit 20 horsepower over a line ½ mile long with a drop of 10 per cent. of the voltage at the receiving end. The voltage at the end of the line is to be 110. Find the size of wire required.

SOLUTION.— 20 horsepower = 20 × 746 watts; hence,

$$\text{current} = \frac{20 \times 746}{110} = 135.6 \text{ amperes}$$

The drop is to be 10 per cent. of the voltage at the receiving end; hence, drop $e = \frac{110 \times 10}{100} = 11$ volts. The length L is 1 mi., since the distance from the station to the end is ½ mi., and applying formula **8**,

$$A = \frac{10.8 \times 5{,}280 \times 135.6}{11} = 702{,}950 \text{ circular mils, nearly. Ans.}$$

This also would call for a large cable.

EXAMPLE 3.—Fig. 2 shows a simple transmission system as used in connection with a street railway. The feeder $a\,c$ runs out from the station and taps into the trolley wire $x\,y$ at the point c. The pressure

between the trolley and track at the point c is to be 500 volts, and the drop in the feeder is to be 10 per cent. of the voltage at the car when a current of 60 amperes is being supplied. The current returns through the track, and we will suppose in this case that the resistance of the return circuit is negligible. Required the cross-section of the feeder $a\,c$.

SOLUTION.—In this case the drop takes place altogether in the wire $a\,c$, because the resistance of the return circuit through the rails is taken as zero; hence, the length L used in the formula will be ¾ mi., or 3,960 ft., and not twice this distance, as in the previous examples. The drop in voltage will be $e = \frac{500 \times 10}{100} = 50$, and since the current is 60 amperes, we have

$$A = \frac{10.8 \times 3{,}960 \times 60}{50} = 51{,}322 \text{ circular mils. Ans.}$$

By referring to the wire table, it will be found that this is nearly a No. 3 B. & S.

20. In making line calculations, it seldom happens that the calculated value will agree exactly with any of the sizes given in the wire table. It is usual in such cases to take the next larger size, unless the smaller size should be considerably nearer the calculated value. Generally, the load operated on a line always tends to increase, because business increases, and it is better to have the line a little large, even if it entails a slightly greater cost when the line is erected.

21. Formula **8** may also be used for determining the drop that will occur on a given line with a given current. In this case the formula is written,

$$\text{volts drop} = e = \frac{10.8\,L\,I}{A} \qquad \textbf{(10)}$$

EXAMPLE.—Power is transmitted over a No. 3 B. & S. line for a distance of 4,000 feet. What will be the drop in the line when a current of 30 amperes is flowing?

SOLUTION.—The length of wire through which the current flows is $2 \times 4{,}000 = 8{,}000$ ft. The cross-section of a No. 3 B. & S. wire is 52,634 circular mils; hence,

$$\text{volts drop} = \frac{10.8 \times 8{,}000 \times 30}{52{,}634} = 49.2. \text{ Ans.}$$

EXAMPLES FOR PRACTICE

1. A dynamo delivers current to a motor situated 850 yards distant. The current taken by the motor at full load is 30 amperes, and the pressure at the motor is to be 220 volts. The drop in the line is to be 8 per cent. of the voltage at the receiving end. Required: (*a*) the drop in volts; (*b*) the size of the wire in circular mils and also the nearest size B. & S.

Ans. $\begin{cases} (a) \text{ 17.6 volts} \\ (b) \text{ 93,886 cir. mils.; use No. 0 wire} \end{cases}$

2. A current of 40 amperes is transmitted from a station to a point 1 mile distant through a No. 0 B. & S. wire: (*a*) What will be the drop, in volts, in the wire? (*b*) How many watts will be wasted in the wire?

Ans. $\begin{cases} (a) \text{ 43.2} \\ (b) \text{ 1,728} \end{cases}$

USE OF HIGH PRESSURE

22. By referring to the first two examples in Art. **19**, it will be noticed that the wire called for is very large, although the amount of power transmitted is not very great nor the distance long. Suppose a fixed number of watts W_s to be transmitted with a given voltage E_s at the end of the line; then, the current that must flow through the line is $\frac{W_s}{E_s}$. We have seen that the loss in the line is $I^2 R$; i. e., if the current be doubled the loss becomes four times as great. If, then, the E. M. F. be doubled, we will be able to transmit the same amount of power with one-half the current, and hence with one-quarter the loss. Or, putting it the other way, and supposing that the loss is to be a fixed amount, we can, by doubling the pressure and thereby halving the current, use a wire of four times the resistance. For example, suppose we have to transmit 20 kilowatts at a terminal pressure of 500 volts and that the loss in the line is to be limited to 2 kilowatts. The current would be $I = \frac{20000}{500} = 40$ amperes, and $I^2 R = 2{,}000$ watts, or $40^2 R = 2{,}000$; hence, $R = \frac{2000}{1600} = 1.25$ ohms. Now, suppose that a terminal pressure of 1,000 volts instead of 500 is used and that the same amount of power is transmitted with the same number of watts loss as before. The current will now be $I = \frac{20000}{1000} = 20$ amperes, and $I^2 R = 2{,}000$ watts, as

before. We will then have $20^2 R = 2{,}000$; $R = \frac{2000}{400} =$ 5 ohms.

In other words, *for the same amount of loss and for the same amount of power delivered, the allowable resistance of the line can be made four times as great if the pressure is doubled.* Since the length is supposed to be the same in both cases, this

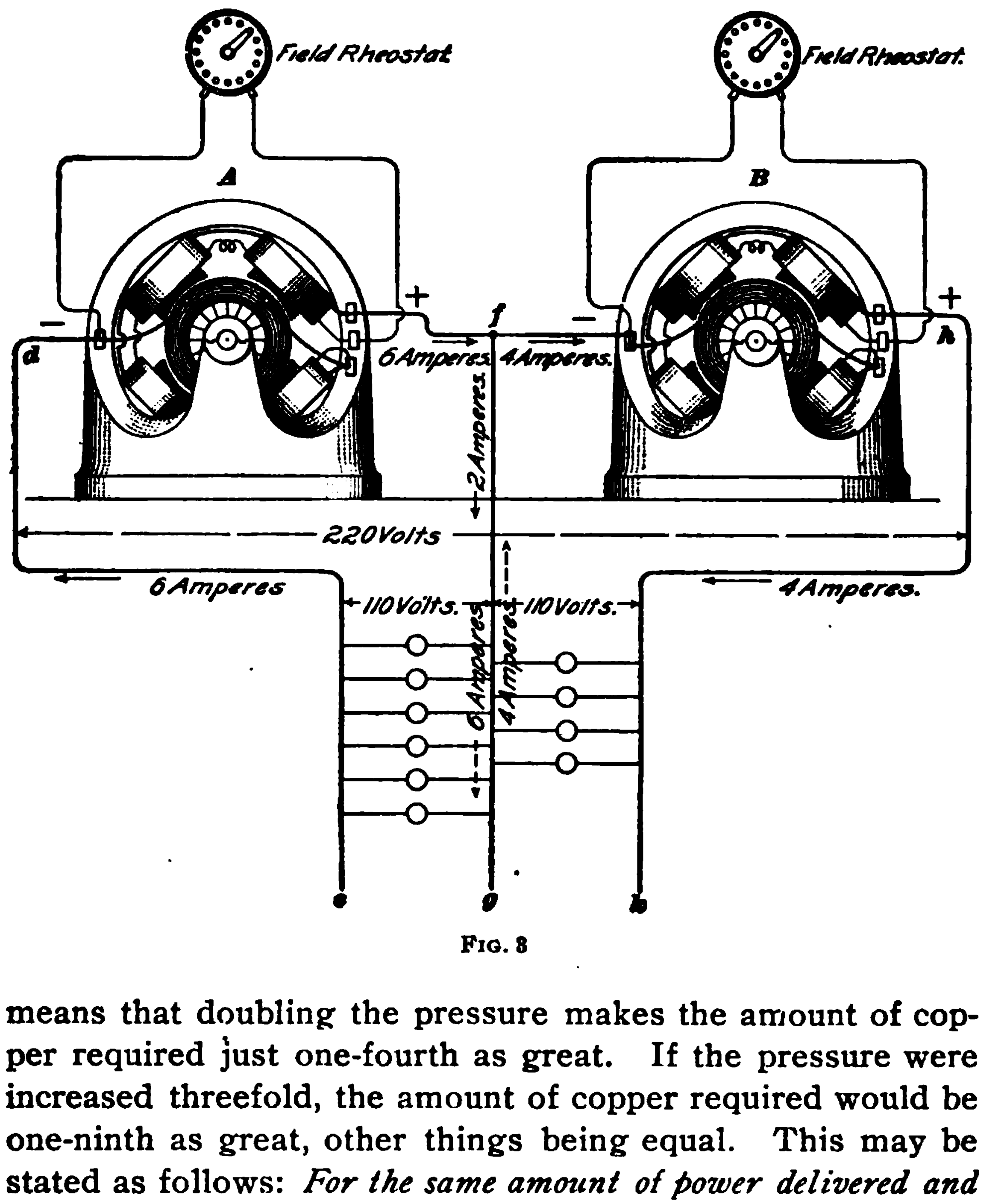


FIG. 8

means that doubling the pressure makes the amount of copper required just one-fourth as great. If the pressure were increased threefold, the amount of copper required would be one-ninth as great, other things being equal. This may be stated as follows: *For the same amount of power delivered and for the same loss in power, the amount of copper required for transmission over a given distance varies inversely as the square of the voltage.*

23. Edison Three-Wire System.—From the preceding it is seen that an increase in the voltage results in a large decrease in the amount of copper required. Incandescent lighting was first carried out at a pressure of 110 volts, but this pressure rendered the use of large conductors necessary, and systems were therefore brought out that would permit the use of a higher pressure. In street-railway work, a pressure of about 500 volts soon became the standard, because this appeared to be the limit to which the voltage could be pushed for this class of work without danger to life.

The **Edison three-wire system** allows current to be supplied at 110 volts, although the transmission itself is really carried out at 220 volts, and therefore results in a large saving in copper over the 110-volt system. The three-wire system is shown in Fig. 3. Two compound dynamos *A* and *B* are connected in series across the two lines *d e* and *h k*. Each dynamo generates 110 volts, so that the pressure between the two outside wires is 220 volts, because the two machines are connected in series. A third wire, called the *neutral*, is connected to the point *f* between the machines, so that between the lines *d e* and *f g* there is a pressure of 110 volts, and between *f g* and *h k* a pressure of 110 volts also.

24. In order to illustrate the action of such a system, suppose there are six 32-candlepower lamps on one side and four on the other, each lamp taking, say, 1 ampere. A current of 4 amperes will flow from the positive side of *B* through the line *h k* and through the lamps to the neutral wire. At the same time, a current of 6 amperes will tend to flow out from the positive pole of *A* over the line *f g* through the left-hand set of lamps and back through *e d*, as shown by the arrows. In the neutral wire there is a current of 6 amperes tending to flow in one direction and a current of 4 amperes tending to flow in the other direction, the result being that the actual current is the difference between the two, or 2 amperes, as shown by the full arrow; or, looking at it in another way, there is 4 amperes flowing directly across from *h k* to *d e* and 2 amperes flowing

from *A* through the neutral wire *f g* and back through *e d* to *A*, thus making 6 amperes in the line *e d*. If the currents taken by the two sides were exactly balanced, no current would flow in the neutral wire and there would be practically a 220-volt, two-wire transmission. In any case, the current in the neutral wire is the difference between the currents in the two sides, and its direction will depend on which side is the more heavily loaded.

25. A three-wire system should always be installed so that the load on the two sides will be as nearly balanced as possible. The simplest way to estimate the size of the conductors is to first calculate the size of the outside wires,

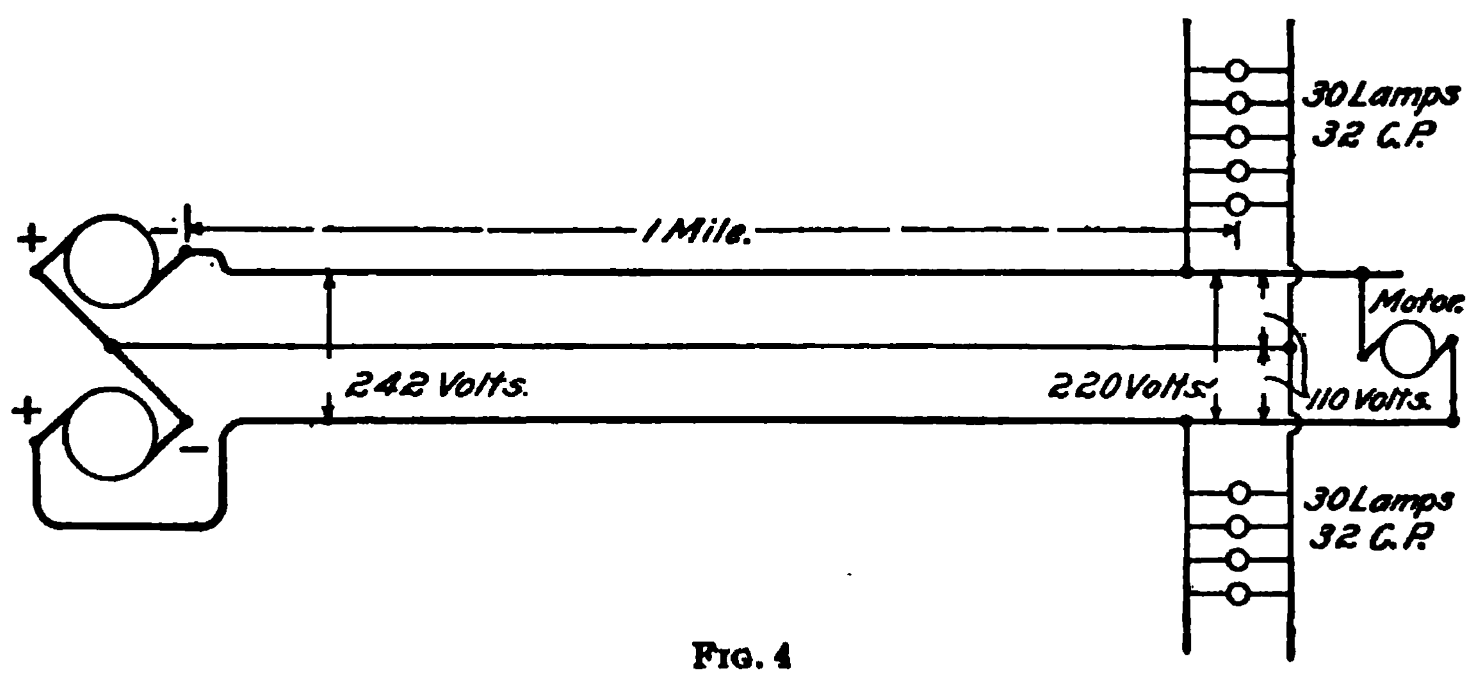


FIG. 4

treating it as if it were a 220-volt, two-wire system. When motors are operated on the three-wire system, they are usually wound for 220 volts and connected across the outside lines. The following example will illustrate the method of calculating the wires for a three-wire transmission:

EXAMPLE.—Two dynamos deliver power over a distance of 1 mile to sixty 32-candlepower lamps, thirty lamps on each side of the circuit, as shown in Fig. 4. A motor that requires a current of 40 amperes is also connected across the outside wires. Each lamp requires a current of 1 ampere, and the pressure at the lamps is to be 110 volts. Calculate the size of wire required for the two outside conductors if the drop in pressure is not to exceed 10 per cent. of the voltage at the end where the power is delivered.

SOLUTION.—The first thing to determine is the current. Thirty lamps are connected on each side and these lamps are connected in

multiple, each taking 1 ampere. The current in the outside lines due to the lamps is, therefore, 30 amperes. The motor is connected directly across the outside lines; hence, the current due to the motor is 40 amperes, and the total current in the outside lines is 70 amperes. The pressure across the outside wires must be 220 volts at the end of the line, because the pressure at the lamps is to be 110. The drop in the outside wires is, therefore, $220 \times .10 = 22$ volts. The length of the outside wires is 2 mi., or 10,560 ft. Applying formula **8**,

$$\text{circular mils} = \frac{10.8 \times 10{,}560 \times 70}{22} = 362{,}880. \quad \text{Ans.}$$

This would require a stranded cable.

26. The neutral wire is often made one-half the cross-section of the outside wires, though practice differs in this respect. It is seldom, however, made less than one-half, and in a number of cases it is made equal in cross-section. Of course, if the load could be kept very nearly balanced at all times, a small neutral wire would be sufficient, but it is impossible to keep the load balanced, and hence it is usual to put in a neutral of at least one-half the cross-section of the outside wires. In the above example, a No. 000 wire would probably be large enough for the neutral. For distributing mains, where there is much liability to unbalancing, the neutral is made equal in size to the outside wires. In some special cases, three-wire systems are arranged so that they can be changed to a two-wire system by connecting the two outside wires together to form one side of the circuit, the neutral wire constituting the other. If this is done, the neutral would have to carry double the current in the outside wires and would be made twice as large as the outside wires.

27. Since the outside wires are only $\frac{1}{4}$ the size required for the same power delivered by means of the two-wire, 110-volt system with the same percentage of loss, it follows that, even if the neutral wire be made as large as the outside wires, the total amount of copper required is only $\frac{1}{4} + \frac{1}{8}$, or $\frac{3}{8}$ of that required for the two-wire, 110-volt system. The amount of copper in the neutral wire is only $\frac{1}{8}$ that required for the two-wire system, because it has $\frac{1}{4}$ the cross-section and its total length is $\frac{1}{2}$ that for the two-wire system.

28. From the preceding it is seen that the three-wire system of distribution effects a considerable saving in copper, owing to the use of a higher pressure. Three-wire systems operating 220-volt lamps with 440 volts across the outside wires have been introduced with considerable success, thus making a still further reduction in copper. The tendency has naturally been to use as high pressure as possible, but there are grave difficulties in the way of transmitting current at high pressure by means of direct current. These difficulties may be classed under the heads (*a*) difficulty of generating direct current at high E. M. F.; and (*b*) difficulty of utilizing direct current at high pressure after it has been generated.

29. Machines for the generation of direct current must be provided with a commutator, and this part of a well-designed machine gives comparatively little trouble if the pressure generated does not exceed 700 or 800 volts; beyond this point, it becomes a difficult matter to make a machine that will operate without sparking. Moreover, in direct-current dynamos, the armature winding has to be divided into a large number of sections or coils, and the numerous crossings of these coils make it exceedingly difficult to insulate such armatures for high pressures.

30. Even if it were possible to generate high-pressure direct current, it would be difficult to utilize it at the other end on account of the danger to life. About 500 to 600 volts is as high as it has been found safe to operate street railways, the consideration of safety setting this limit on the pressure used. Moreover, it is just as difficult to build motors for high-pressure direct current as it is dynamos, and for most purposes the high-pressure current would have to be reduced to low pressure before it could be utilized with safety at the distant end of the line. This transformation could be effected by using a high-voltage motor to drive a low-voltage dynamo. In some cases, these two machines might be combined into one having an armature provided with two windings and two commutators, this armature being arranged so as to revolve

in a common field magnet. The high-tension current from the line is led into one winding through one commutator and drives the machine as a motor. The second set of windings connected to the other commutator cuts across the field and sets up the secondary E. M. F., thus applying current to the low-pressure lines. A machine of this kind is known as a **dynamotor**. It is thus seen that the transformation of direct current from high pressure to low pressure involves the use of what is essentially a high-pressure, direct-current motor—a piece of machinery that is liable to give more or less trouble for the reasons already stated.

SPECIAL THREE-WIRE SYSTEMS

31. The ordinary three-wire system requires two dynamos, and a number of special systems have been devised whereby a three-wire system may be operated from a single machine. Some of these systems will be found described in

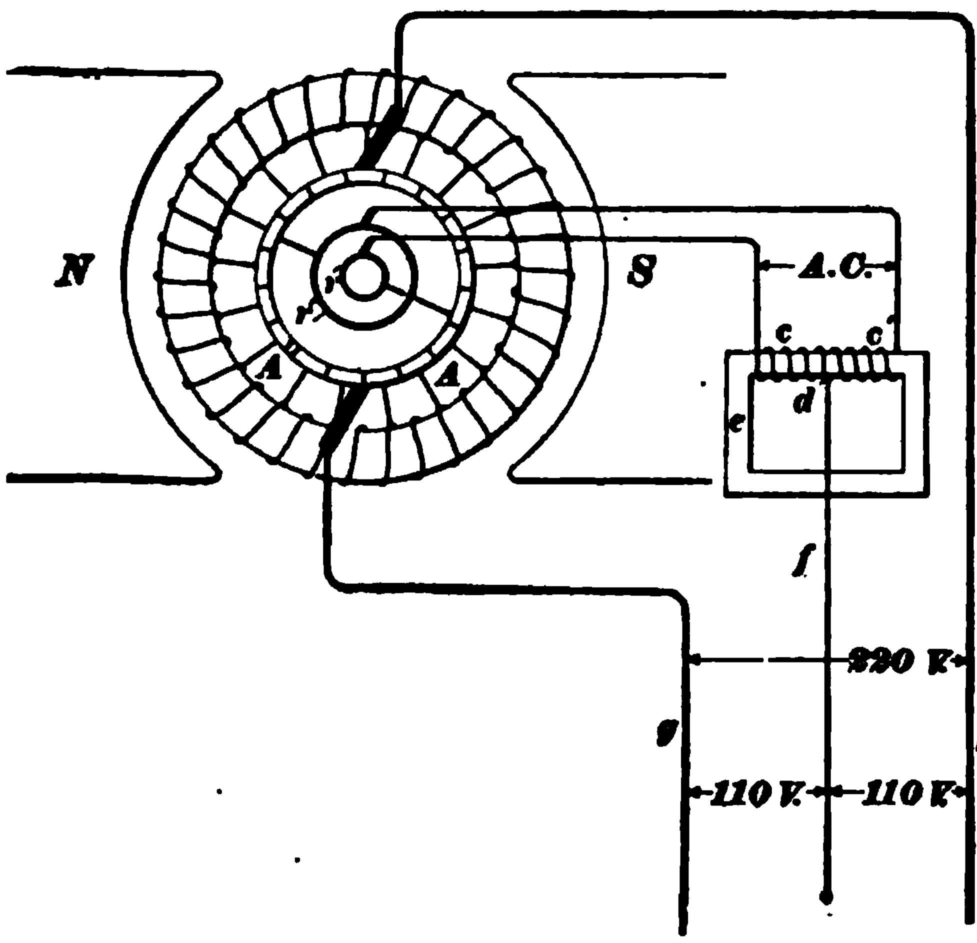


FIG. 5

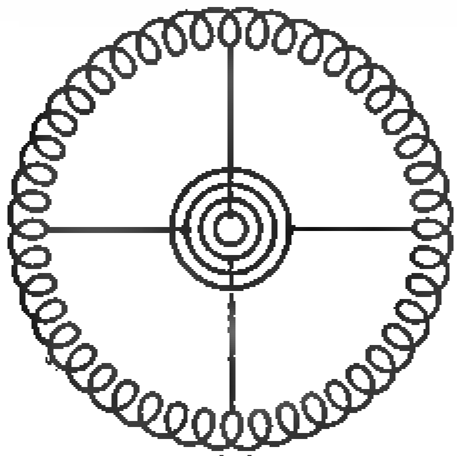
connection with *Electric Lighting*. Perhaps the most common method, outside of the regular system using two machines, is the use of a single large dynamo connected across the outside wires and a balancing set consisting of a pair of small

machines connected in series across the lines to take care of the unbalanced portion of the load, the neutral wire being connected between the machines, as described in *Electric Lighting*.

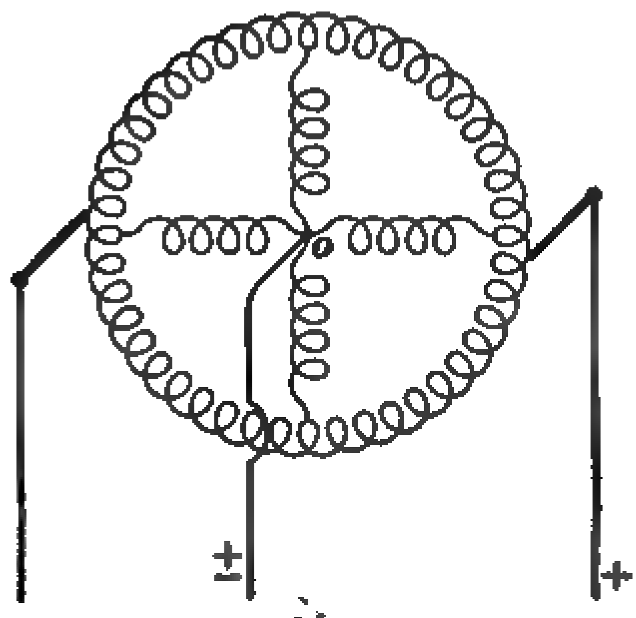
32. Dobrowolsky Three-Wire System.—Fig. 5 shows a method invented by Dobrowolsky for running a three-wire system from a single dynamo. *A A* is an ordinary direct-current armature connected to its commutator in the usual manner. Two diametrically opposite points of the winding are connected to the rings *r*, *r'*, and from these connection is made to the terminals of a choke coil. The coils *c*, *c'* have an equal number of turns, and as they are wound on the laminated iron core *e*, they have a high inductance. The pressure applied to the terminals of *c*, *c'* is alternating, because connection is made to the armature winding through slip rings *r*, *r'*. Since the E. M. F. applied to *c*, *c'* is alternating, the coils will not short-circuit the armature because of the counter induced E. M. F. Also, since *c* and *c'* have an equal number of turns, the point *d* will always be at a potential midway between that of the two terminals attached to the collector rings, and if the neutral wire *f* is attached to the junction of *c* and *c'*, the pressure between *f* and either outside wire will be one-half that between the outside wires. If the system becomes unbalanced, a direct current flows through *f*, but the choke coil offers no opposition other than the slight ohmic resistance of *c* and *c'*, because this current is steady and cannot therefore set up a counter E. M. F. Also, if a direct current flows into the coils through *f*, it divides, half flowing through *c* and half through *c'*, and since the two parts of the direct current circulate around the core in opposite directions, the magnetizing effect of the direct current is zero, and it does not therefore interfere with the choking effect that the coils exert on the alternating current.

33. Fig. 6 shows how this system has been applied by the Westinghouse Company. In order to get a more uniform action, the winding is tapped at four points, as in Fig. 6 (*a*), and these points connected to four collector rings in exactly

the same way as for a quarter-phase rotary converter, the commutator and brushes being here omitted. The four rings A_1, B_1, A_2, B_2, Fig. 6 (*b*), are connected to the choke coils C_1, C_2, and the mid-points *x* of each coil, or rather pair of coils, are connected to the neutral wire *a*. If the choke coils could be mounted in the armature and revolved with



(*a*)



(*c*)

FIG. 6

it, the connections would be equivalent to those shown in Fig. 6 (*c*), and but one collector ring would be required to connect the neutral wire with the neutral point *O*. In some cases three pairs of choke coils are used connected to six equally spaced points in a manner similar to that shown in Fig. 6 (*a*), each point connecting to a collector ring. The

diagrams are here shown for two-pole machines; for multipolar machines there would be a connection to each ring for each pair of poles.

34. Fig. 7 shows a method of operating a three-wire, direct-current system from two-phase, alternating-current mains. An arrangement of this kind is useful where the greater part of the output of a plant is utilized as alternating current, but where it is desired to use part of it for operating direct-current motors on the three-wire system or supply an existing three-wire, direct-current system from an alternating-current station. *A* and *B* are two transformers with their primaries connected to the two phases and their secondaries connected in series and feeding a two-phase, three-wire rotary converter. The mid-point *C* of the two secondaries is connected to the neutral wire *N*. The pressures between *C* and *D* and between *C* and *E* are equal; but the pressure between *E* and *D* is 1.414 times the pressure between either *C* and *D* or *C* and *E*, since a two-phase system is used.

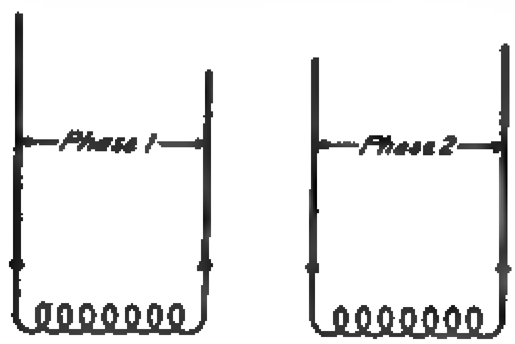


FIG. 7

The pressures between the neutral wire *N* and either of the two outside direct-current line wires *F* or *G* are equal and are one-half the value of the electromotive force between wires *F* and *G*.

35. Direct-Current Converter.—Referring again to Fig. 5, it will be seen that instead of driving the armature *A* by means of a belt and thereby operating a three-wire system from a single dynamo, the armature may be driven

by means of current supplied from an outside source. When operated in this way the machine acts as a direct-current converter, and by means of it direct current can be transformed to another direct current at half the voltage, or the current supplied can be delivered as another at twice the original voltage. For example, in Fig. 5, current at 220 volts can be supplied at the brushes and a current of twice the amount delivered at 110 volts. Or, if current is supplied at 110 volts to one pair of the three terminal wires, it will be converted to a current of one-half the volume at 220 volts. Direct-current converters have been used in some cases where it is desired to operate 250-volt motors from a 500-volt power circuit. These machines have so far been used but little for this class of work, motor dynamos or dynamotors having been used instead.

POWER TRANSMISSION BY ALTERNATING CURRENT

36. The difficulties encountered in the generation and utilization of high-tension direct current led engineers to adopt **alternating current** for places where the power had to be transmitted over considerable distances. At first, alternating current was used for lighting work only, because the single-phase alternators first introduced were not capable of readily operating motors, although they were quite satisfactory for the operation of incandescent lamps. With the introduction of polyphase alternators along with the induction motor, the use of alternating current for power purposes became very common, and plants using line pressures as high as 60,000 volts are in regular operation.

37. Alternating current is well adapted for high-pressure work, because not only can it easily be generated, but what is even of greater importance, it can be readily transformed from one pressure to another. The winding of an alternator armature is very simple, no commutator is necessary, and the problem of generating high pressures becomes a

comparatively easy one. In some cases, the current is generated at a low pressure and raised by step-up transformers for transmission over the line. At the distant end it is easily lowered, by means of step-down transformers, to any pressure required for the work to which it is to be put.

SINGLE-PHASE TRANSMISSION

38. The simplest scheme for alternating-current transmission is that which uses a single-phase dynamo; i. e., a machine that generates a single alternating current. In Fig. 8, *A* represents a simple alternator generating current at a high pressure. This current is transmitted over the line to the distant end, where it is sent through the primary of transformer *B*, which lowers the pressure to an amount suitable for distribution to the lamps *l*. The synchronous motor *M* is operated directly from the line, because it can be wound for a high voltage. If, however, this high pressure about the motor should for any reason be objectionable, step-down transformers could be used. As already mentioned, such systems are installed for lighting work almost exclusively. At first a pressure of 1,100 volts at the alternator, or about 1,000 at the end of the line, was commonly used. Later, pressures of 2,200 and 2,000 volts became the ordinary practice. In cases where the distance was very long, step-up transformers were used, as shown in Fig. 9. Here the current from the alternator *A* is first sent into the primary of the transformer *T*, which raises the voltage to any required amount, with, of course, a corresponding reduction in current. At the other end, the transformer *T'* steps down the high line pressure to whatever pressure is suitable for local distribution.

39. The single-phase system has been used in the past to a limited extent for the operation of synchronous motors. The ordinary single-phase synchronous motor will not start up even if it is not loaded and this is a great drawback to its use. The single-phase system is therefore seldom installed where power is to be transmitted for the operation

Fig. 8

Fig. 9

of alternating-current motors of large size. The motor *M* shown in Fig. 8 is the same in construction as an alternator, but it would have to be provided with some arrangement for bringing it up to speed. It is possible that in the future single-phase, alternating-current motors may be so improved that this system will be used much more largely for power purposes than it is now. Experiments have already been made in the operation of electric railways by means of single-phase motors constructed similar to series direct-current motors, but having laminated fields. The results obtained have been so satisfactory that a large increase in the use of single-phase current for power purposes may be expected, though at present the single-phase series motor has not been used to any great extent in regular commercial work.

TWO-PHASE POWER TRANSMISSION

40. The great advantage of the two-phase system over the single-phase is that it allows the operation of rotary-field induction motors and two-phase synchronous motors. Fig. 10 shows a two-phase system. In this case, we have taken the simplest arrangement, where the alternator feeds directly into the line without the use of step-up transformers. If, however, the distance is very long, step-up and step-down transformers could be connected in each phase, in a manner similar to that shown in Fig. 9. *A* is the alternator supplying the two currents differing in phase by 90° to the four line wires. *B*, *B* are two transformers supplying lights. One is connected on phase No. *1* and the other on phase No. *2*, so as not to unbalance the load on the alternator. *C*, *C* are two large transformers supplying alternating current at 389 volts to the rotary transformer *D*, which changes it to direct current at 550 volts suitable for operating the street-railway system *E*. *F*, *F* are two transformers supplying a two-phase induction motor *G*. *H* shows a two-phase synchronous motor. This is the same in construction as the generator *A*, and it is not necessary to use transformers with it, as it can be constructed for the same voltage as the generator.

Fig. 10

THREE-PHASE POWER TRANSMISSION

41. In the three-phase system, if the load on all three phases is kept nearly balanced, as it usually is in practice, only three wires are needed. For the same amount of power, line loss, and distance of transmission, the three-phase system requires only three-fourths the amount of copper called for by the single-phase or two-phase systems. For this reason, it is often used for the transmission itself, even if the power is generated by means of two-phase alternators. By a special arrangement of transformers, described later, two currents differing in phase by 90° can be transformed into three differing in phase by 120°. Fig. 11 is similar to Fig. 10, except that it is arranged for a three-phase transmission. There is little choice between the two-phase and three-phase systems so far as actual operation is concerned, the chief point in favor of the three-phase system being the saving in line wire.

42. In many large transmission systems, it is customary to generate the power in one large central station and distribute it at high pressure to a number of substations located at the various distributing centers. At these substations the current is transformed down and passed through rotary converters, if direct current is necessary, and distributed to the various devices to be operated. This is commonly done in connection with both lighting and street-railway work. If alternating current alone is used, the voltage is merely stepped down by means of large transformers.

At present, the three-phase system is the one most largely used for power transmission purposes. When the power is used for railway operation, the alternating current is changed into direct current, because heretofore alternating-current motors have not proved as satisfactory as direct-current motors for railway operation, hoisting, or other variable speed work. However, recent developments in the line of the single-phase series motor with laminated field seem to indicate that motors of this or similar type can be built so as

Fig. 11

to have sufficiently large output and at the same time run without sparking. These motors have properties much the same as series-wound, direct-current motors. They give a good starting torque and are well adapted to variable speed. A great deal of experimenting is at present being done with them, and it is probable that the single-phase system will, in the future, be a strong competitor of the two-phase and three-phase systems for railway work.

LINE CALCULATIONS FOR ALTERNATING CURRENT

43. The factors that determine the size of line wire for a direct-current transmission apply also, in a general way, to alternating-current systems. The resistance of the line causes a drop in pressure between the station and the distant end, and the line must be proportioned so that this drop will not be excessive. If the load to be carried is practically non-inductive, and if the distances are not long, the same rules that have already been given for direct-current circuits may be applied with sufficient accuracy to alternating-current lines. If, however, the lines are long, say more than 2 or 3 miles, there are other effects that must be taken into account. It must be remembered that the current is continually changing, and this introduces effects not met with in continuous-current circuits where the current flows steadily in one direction. The size of wire required will depend not only on the amount of the load, but also on the kind of load, i. e., on whether it consists wholly of motors or lights, or a combination of the two. In direct-current circuits, it makes no difference, so far as the drop in the line is concerned, how far the wires are strung apart on the poles, but in an alternating-current circuit this may have an appreciable effect.

The effects of self-induction and capacity on alternating-current transmission lines have already been given in connection with the subject of alternating currents. On all but very long transmission lines the effects of capacity are not serious, but the inductance of the line may have quite a large

influence on the line drop. The relation between the line drop, terminal E. M. F., and generator E. M. F. has been shown by means of an E. M. F. diagram, and by laying out such a diagram, the size of wire for any particular case could be obtained. For ordinary line calculations, however, it is convenient to use formulas that may be easily applied, and that will give results accurate enough for most practical purposes.

FORMULAS FOR LINE CALCULATIONS

44. Estimation of Cross-Section of Lines.—In a direct-current transmission line a certain drop in voltage is equivalent to a corresponding loss in power. With alternating current, the percentage drop in pressure may be quite different from the percentage loss in power. In case alternating current is used, the drop in voltage will very likely be more than the corresponding loss in power, because of the self-induction of the line. Just what the drop will be, corresponding to a given loss in power, depends on the size of the wire, distance apart on the poles, etc. The exact calculation of line wires for alternating current is a complicated matter, but in nearly all the cases that arise in practice they can be estimated with sufficient accuracy by means of comparatively simple formulas. The following formulas, originated by Mr. E. J. Berg, will be found convenient for estimating alternating-current lines. The different quantities entering into the calculations are as follows:

D = distance in feet over which power is transmitted (this distance is to be taken one way only, i. e., it is the single distance);

W_2 = total watts delivered at the end of the line (this number must express the actual watts delivered, not the apparent watts);

P = percentage of power lost in line (it should be noted that this percentage is that of the power delivered, not the power generated; also, it is the percentage power lost, not the percentage drop in voltage);

E_s = voltage required at the receiving end of the line, i. e., the voltage at the end where the power is delivered;

t = a constant having the following values:

2,400 for a single-phase system operating lights only;

3,000 for a single-phase system operating motors and lights;

3,380 for a single-phase system operating motors only;

1,200 for a three-wire, three-phase and four-wire, two-phase system, all lights;

1,500 for a three-wire, three-phase and four-wire, two-phase system, motors and lights;

1,690 for a three-wire, three-phase and four-wire, two-phase system, all motors.

The cross-section of the wire required for any given case may then be calculated from the following formula:

$$\text{circular mils} = \frac{DW_s t}{PE_s^2} \qquad (11)$$

EXAMPLE.— 300 horsepower is to be transmitted by means of the three-phase system over a distance of 5 miles with a loss of 10 per cent. of the power delivered. The pressure at the end of the line is to be 4,000 volts and the power is to be used altogether for operating motors. Calculate the size of line wire required.

SOLUTION.—In this case the distance D is $5{,}280 \times 5 = 26{,}400$ ft. The watts delivered will be $300 \times 746 = 223{,}800$. $P = 10$ and $E_s = 4{,}000$. The constant t for this case will be 1,690; hence, we have from formula

$$\text{circular mils} = \frac{26{,}400 \times 223{,}800 \times 1{,}690}{10 \times 4{,}000 \times 4{,}000} = 62{,}407,$$

or about a No. 2 B. & S. Ans.

45. Estimation of Current in Lines.—The current in the line wires of an ordinary direct-current line is easily obtained by dividing the watts delivered by the voltage at the end of the line. The current in the case of alternating-current systems can be calculated by using a similar formula and multiplying by a constant, to allow for the circumstances under which the current is used, as follows:

$$\text{current in line} = \frac{W_s T}{E_s} \qquad (12)$$

where W_s = watts delivered;
E_s = voltage at the receiving end of the line;
T = constant referred to above.

VALUES OF CONSTANT T

Single-phase system, all lights	1.052
Single-phase system, motors and lights	1.176
Single-phase system, all motors	1.250
Two-phase, four-wire system, all lights	.526
Two-phase, four-wire system, motors and lights	.588
Two-phase, four-wire system, all motors	.625
Three-phase system, all lights	.607
Three-phase system, motors and lights	.679
Three-phase system, all motors	.725

EXAMPLE 1.— 100 kilowatts is delivered by means of the two-phase, four-wire system to a mixed load of motors and lights. The pressure at the receiving end of the line is 2,000 volts. Calculate the current in each line wire.

SOLUTION.— 100 K. W. = 100,000 watts. For this case the constant T will be .588; hence,

$$\text{current} = \frac{100{,}000 \times .588}{2{,}000} = 29.4 \text{ amperes. Ans.}$$

EXAMPLE 2.— 200 kilowatts is transmitted by means of the three-phase system, the voltage between lines at the receiving end being 4,000 volts. The load consists wholly of motors; calculate the current in each line.

SOLUTION.— 200 K. W. = 200,000 watts. For this case the value of T will be .725; hence,

$$\text{current} = \frac{200{,}000 \times .725}{4{,}000} = 36.25 \text{ amperes. Ans.}$$

46. Estimation of Drop.—The volts drop in the line for a continuous-current system would be $\frac{P E_s}{100}$, when P is the percentage of delivered power lost and E_s is the voltage at the receiving end of the line. This formula can be made to give the approximate drop in an alternating-current line by multiplying it by a constant that takes into account the conditions under which the line is operated, as follows:

$$\text{volts drop in line} = \frac{P E_s M}{100} \qquad (13)$$

The value of M depends on the frequency, the power factor of the load, and the size of the line wire; its value, under various conditions, is given in the following table:

TABLE II

No. of Wire B. & S. Gauge	Area, Circular Mils	Values of M								
		30 Cycles			60 Cycles			125 Cycles		
		Lights Only	Motors and Lights	Motors Only	Lights Only	Motors and Lights	Motors Only	Lights Only	Motors and Lights	Motors Only
0000	211,600	1.26	1.27	1.24	1.64	1.85	1.85	2.44	3.06	3.14
000	167,805	1.20	1.17	1.14	1.49	1.63	1.62	2.15	2.62	2.67
00	133,079	1.15	1.08	1.05	1.39	1.46	1.42	1.92	2.25	2.29
0	105,535	1.10	1.00	1.00	1.30	1.32	1.28	1.73	1.96	1.99
1	83,694	1.06	1.00	1.00	1.23	1.21	1.16	1.57	1.74	1.73
2	66,373	1.03	1.00	1.00	1.16	1.11	1.06	1.44	1.54	1.53
3	52,634	1.02	1.00	1.00	1.11	1.04	1.00	1.35	1.38	1.38
4	41,742	1.00	1.00	1.00	1.07	1.00	1.00	1.26	1.26	1.22
5	33,102	1.00	1.00	1.00	1.04	1.00	1.00	1.19	1.16	1.11
6	26,251	1.00	1.00	1.00	1.02	1.00	1.00	1.14	1.08	1.03
7	20,816	1.00	1.00	1.00	1.00	1.00	1.00	1.09	1.01	1.00
8	16,509	1.00	1.00	1.00	1.00	1.00	1.00	1.06	1.00	1.00

EXAMPLE.— 600 kilowatts is to be transmitted a distance of 6 miles by means of the three-phase 60-cycle system. The loss in the line is to be limited to 10 per cent. of the power delivered, and the pressure at the receiving end of the line is to be 6,000 volts. The current is to be supplied to a mixed load of motors and lights. Calculate: (*a*) the size of the line wire; (*b*) the current in each line; (*c*) the volts drop in the line; and (*d*) the pressure generated by the dynamos at full load.

SOLUTION.—(*a*) 600 K. W. = 600,000 watts. 6 mi. = 6 × 5,280 = 31,680 ft. Using formula **11**, we have, since t for this case is 1,500,

$$\text{circular mils} = \frac{31{,}680 \times 600{,}000 \times 1{,}500}{10 \times 6{,}000 \times 6{,}000} = 79{,}200$$

A No. 1 B. & S. wire would therefore be used. Ans.

(*b*) In order to obtain the current in each line we use formula **12**, and for this case, the value of T will be .679; hence,

$$\text{current} = \frac{600,000 \times .679}{6,000} = 67.9 \text{ amperes. Ans.}$$

(*c*) In order to calculate the volts drop in the line, we use formula **13.** For a No. 1 wire and a frequency of 60 cycles on a combined lamp and motor load, the value of the constant M is found to be 1.21 by referring to the table; hence,

$$\text{volts drop} = \frac{10 \times 6,000 \times 1.21}{100} = 726. \text{ Ans.}$$

(*d*) Since the drop in the line is 726 volts, the pressure at the dynamo must be $6,000 + 726 = 6,726$ volts when the full-load current is being delivered. Ans.

NOTE.—In the above example, the drop in the line would have been only 600 volts if continuous current were used.

EXAMPLES FOR PRACTICE

1. 250 horsepower is to be supplied to 60-cycle induction motors by means of the two-phase, four-wire system over a line 3 miles long. The pressure at the distant end of the line is to be 4,000 volts and the loss in the line is to be limited to 8 per cent. of the power delivered. Calculate: (*a*) the size of the wire required; (*b*) the current in each line wire; (*c*) the drop in the line.

Ans. (*a*) 39,000 cir. mils, nearly; about No. 4 B. & S.
(*b*) 29.14 amperes
(*c*) 320 volts

2. A three-phase alternator delivers 400 horsepower to a mixed load of motors and lights. The pressure at the distant end of the line is 3,000 volts. Calculate the current in each line. Ans. 67.54 amperes

3. 5,000 incandescent lamps are supplied with current from a single-phase alternator, having a frequency of 125, over a distance of 3 miles. The loss in the line is to be limited to 10 per cent. of the power delivered, and the pressure at the end of the line is to be 3,000 volts. Allow 60 watts for each lamp supplied and calculate: (*a*) the size of the line wire; (*b*) the current in the line; (*c*) the volts drop in the line; (*d*) the voltage at the generator.

Ans. (*a*) 126,720 cir. mils, or about No. 00 B. & S.
(*b*) 105.2 amperes
(*c*) 576 volts
(*d*) 3,576 volts

THE SELECTION OF A SYSTEM

47. From the foregoing it is seen that the engineer has a large number of systems to choose from when installing a given plant, and the selection of a system for any given case is a matter that requires careful consideration. We will, therefore, endeavor to sum up the principal advantages and disadvantages of the different systems as an aid in determining the system to be used in any given case.

The selection of a system, so far as its bearing on the location of the station is concerned, is comparatively unimportant in ordinary street-railway work, as the 500-volt, direct-current system is the standard American practice, due allowance being made for distance. But in the case of lighting and power distribution over large districts, and for long-distance railway work, the problems require careful analysis.

DIRECT-CURRENT SYSTEMS

48. If lighting and motive power are required, the first points to be considered are the characteristics of the town and nature of the business to be expected. In compactly built, thickly settled places, where a good site for a station can be had within a mile from the most distant lights or motors, there is no better or cheaper system, either in first cost, economy, or convenience of operation than the **direct-current system**, and whether it should be two- or three-wire, circumstances will dètermine. Where distances exceed 1 mile, boosters can be used advantageously, or the double-bus system of high and low potential. These last two arrangements are described more in detail later. In the following we will state the potential on the system of distribution, and due allowance must be made for drop in E. M. F. between generators and the point where the energy is utilized.

49. The **two-wire, 220-volt system** is in successful operation, and the 220-volt incandescent lamp is perfected for use on a commercial basis. There can be no question of the great advantage of a 220-volt, two-wire system over the three-wire system in simplicity and reduced cost of copper. It must be recognized, however, that greater care is required in insulating and installing all interior fittings that require more or less handling.

50. Three-Wire, 220-Volt System.—The advantages of the three-wire, 220-volt, direct-current system are many, among which may be mentioned the following; some of these also apply to the 220-volt, two-wire system.

1. Low potentials in dynamos, station apparatus, and street lines, and consequent perfect safety to the dynamo attendants, linemen, and the public.

2. Greatly lessened leakage, and therefore reduced risk from fire.

3. Convenience, cheapness, and ease of connection to the wiring on the consumers' premises.

4. The reading at the station, of pressure returned from extreme feeder ends by means of pressure wires, as described later, indicates quite accurately the pressure at the consumers' premises.

5. As the dynamos are run in parallel on the system in conjunction with station methods of regulation and control, it is possible to tie the mains and feeders together wherever convenient, thus insuring by equalization a more uniform pressure, no matter to what extent the electrical center or heavy load in the district may shift during the 24 hours. By enabling the lightly loaded lines to supplement those that are heavily loaded, this system of intermeshing conductors equalizes the potential and gives the best results from a given weight of copper.

6. The use of direct current makes possible the employment of storage batteries as an adjunct to the central station, thus lessening the hours during which it may be necessary to operate a considerable portion of the steam plant, minimizing

the labor account, and enabling one to run the boilers, engines, and dynamos at a higher efficiency during the period they are in operation, and to shut them down as soon as the load is low enough to justify throwing all or a portion of it on the storage battery. Moreover, in case of a sudden or heavy demand for extra current, such as may be occasioned by bad weather or sudden thunder storm, the battery is always on hand, ready to be thrown on instantly to supplement the dynamos, whereas it requires some time to start an idle engine and throw in its dynamos.

7. Electrolytic and electroplating work can be done with the direct current, but is impossible with alternating currents, except at considerable expense and complication for rotary converters or other transforming devices.

8. The measurement of power, calculation of conductors, and arrangement of circuits are simpler than in the alternating system, on account of the absence of induction and consequent lag effects.

9. Simple and efficient motors are readily installed and operated, and form a considerable source of income.

10. The broad establishment of the business, the vast amount already served by the three-wire system, and its standardized methods largely influence its adoption.

But the three-wire system has manifest disadvantages, the most prominent of which are as follows:

1. The two sides of the system must be kept at nearly equal loads, as want of balance occasions a difference in potential between the positive and negative sides, and consequently a difference in the brilliancy of the lights.

2. If overhead lines are used for large currents, they are cumbersome, costly, and extremely liable to disaster from high winds or lightning.

3. It is impossible to cover a very large extent of territory at 250 volts potential without great expense for copper.

4. A ground on any part of the wiring, no matter how trifling in itself, may be a fault on the whole system, and if not promptly eliminated may give rise to a bad short circuit.

5. Switchboard and other connections are complicated because of the use of three wires and the operation of the dynamos in pairs connected two in series.

51. Three-Wire, 500-Volt System.—A larger extent of territory can be served by the use of the three-wire, 250–500-volt, direct-current system because it has greater capabilities of expansion, with less investment in copper for lightly loaded or scattered territory, as well as requiring less copper in heavily loaded business districts. The advantage stated for the 500-volt, three-wire system with the same current distribution and the same station location, is that it will cover, at the same cost of copper, a territory four times as large as with a 250-volt, three-wire system. Increased risks are encountered as mentioned, as regards insulation within buildings and for underground distributing systems because of higher potential, but these conditions are successfully met by the employment of standard appliances. The important point is that the ignorant consumer shall be fully protected when current is supplied him at potentials bordering on the danger line.

ALTERNATING-CURRENT SYSTEMS

52. The **alternating-current system** has great value in the special field of transmission for long-distance and house-to-house supply in scattered territories, and is excellent and comparatively economical as a temporary expedient for developing business in a new territory. Before alternating current can be used in compact territory in combination with, or to replace, direct current, the following improvements are necessary:

1. A type of motor must be developed that will meet all commercial requirements, which can be used successfully for all classes of business without causing disturbance of the fixed potential of the system.

2. A universal system of supply that does not require transformers or anything except a meter to be located on the premises of the customer.

3. Some type of apparatus that will replace the storage battery as used in connection with direct current.

Alternating current cannot be used in connection with storage batteries, except through the employment of a rotary converter or motor generator for charging the battery. The use of such converting apparatus will be justified when the amount of current supplied and compensation received is sufficiently large to overbalance the extra cost for special equipment and the losses incurred for conversion of energy.

The direct-current motor can be better applied for general power work, and in some respects is superior to the alternating-current motor in its electrical operation. The disturbing effects on the system are less, when starting and stopping large motors. The initial cost of direct-current motors and their few necessary auxiliaries is much less than that of alternating-current motors. Alternating-current induction motors, on the other hand, have the advantage over direct-current of not requiring a commutator and brushes. Direct current is best adapted for elevator work.

With direct current at least 80 per cent. of the manufactured power can be accounted for through the meters on a good system, whereas with the alternating-current system, from 50 per cent. to 60 per cent. only of the power can be accounted for; the rest is lost in transformers and special devices.

The comparative usefulness of the two systems for commercial distribution is illustrated in Chicago, where with a maximum output of 25,000 kilowatts, 20.4 per cent. is for 60-cycle distribution covering a territory of 58 square miles, and 79.5 per cent. is for direct-current distribution over a territory of 10 square miles.

The concensus of expert opinion is that the alternating-current system has not attained the requisite degree of perfection for general distribution, in compact territory, though for long-distance work it is indispensable. In compact territory it cannot be used with storage batteries; the motor cannot be used for general power purposes. It is therefore

evident that there is not yet any single ideal system that can be universally applied to serve all local conditions; special requirements, the environment of the station, and relative commercial importance of the various classes of service must be taken into account in determining what is most desirable for each given locality.

53. The problem for a combination system may, for example, be solved as follows:

For incandescent lighting and motive power in the business and near-by residential districts, the three-wire, direct-current system, 220 volts.

For incandescent lighting and some classes of motive power in scattered and long-distance territory, the alternating-current system, 2,300 volts primary; 110 to 220 volts secondary.

For arc lighting in streets, the enclosed series-arcs on the alternating-current system.

If the bulk of the power is transmitted over a long distance, or supplied to a widely scattered area, the two-phase or three-phase systems would be installed; that is, only one kind of current would be furnished from the station, and if direct current were essential for any special purpose, it would be transformed at the consumers' premises by means of a rotary converter.

In general, it is well to avoid too great a variety of apparatus in a station, because it necessitates several sets of duplicate machines. Considerations of economy are frequently sacrificed in order to make the generating units in a given station uniform as to size and output.

FREQUENCY

54. The choice of a proper **frequency** in alternating-current systems is important. The early single-phase plants were designed for from 125 to 150 cycles, and some polyphase machines have been built for these frequencies. The high inductive effects, troubles in parallel operation, and the

difficulty of obtaining low speeds have caused such high frequencies to be abandoned in favor of 60 cycles or less. In polyphase plants, therefore, 60, 40, and 25 cycles have come to be the standard frequencies. The choice of frequency should be governed by a careful consideration of the apparatus to which the plant is to furnish power.

If the alternating current is to be used for lighting purposes only, a high frequency affords the advantage of low first cost, and such a system might be even single phase. However, the demand for electric power is now so great that a low-frequency polyphase system is nearly always used in modern alternating-current installations. The cost of transformers, per kilowatt, diminishes as the frequency increases and this is one of the reasons why high frequency was used in the early installations when belt-driven, high-speed alternators were used almost exclusively. With the introduction of slow-speed, direct-driven machines, low frequencies became desirable, and the increasing use of induction motors, synchronous motors, and rotary converters also led to the introduction of lower frequencies. A frequency of 60 cycles is suitable for incandescent lighting, arc lighting, and some motive power. When the current is used nearly altogether for power purposes, it is better to use lower frequency; 60 cycles will only be found satisfactory with synchronous motors, rotary converters, and similar apparatus when the speed regulation of the motive power is very good, because of the hunting or periodic surgings in speed that are liable to occur. A frequency of 40 cycles permits current for both lighting and power purposes to be supplied to advantage. It is within the limit of reasonable safety for operating rotary converters and is the lowest limit for satisfactory working of incandescent and arc lights; 40-cycle equipments are not in general use and should only be adopted after analyzing all anticipated or existing conditions and finding that 60 cycles cannot be used with reasonable safety. A frequency of 25 cycles is very commonly used where the current is supplied wholly for power purposes.

COST OF CONDUCTORS

55. In order to determine the best potential for a power transmission, it is necessary to consider carefully the cost of the transmission circuit. The weight of the conductor varies inversely as the square of the voltage, and varies directly as the square of the distance. Dividing the potential by the distance gives a convenient figure, which can be used for all potentials and distances. The curves on the diagram, Fig. 12, given by the General Electric Company, furnish a ready means of obtaining the amount of copper required for a given power transmission. The figures on the curves indicate volts per mile; i. e., potential of line at generator divided by distance in miles. The weight of copper, potential, and line loss are in terms of the power delivered at the end of the line, and not of generated power. The curves are correct only for three-phase current with 100 per cent. power factor. Two-phase, single-phase, or continuous-current transmission requires one-third more copper. Five per cent. has been allowed for sag and waste in weights of copper given.

EXAMPLE.—If copper is worth 15 cents per pound, what will the cost of copper be for a line (three-phase) to transmit 1,000 kilowatts at 10,000 volts over a line 10 miles long, with a loss of 5 per cent. of the delivered power?

SOLUTION.—Since 1,000 K. W. at 10,000 volts is to be delivered over a line 10 mi. long with 5 per cent. loss, we have $\frac{10{,}000 \text{ volts}}{10 \text{ mi.}} = 1{,}000$ volts per mi. Looking on the 1,000-volt curve, we find 5 per cent. loss corresponds to 57 lb. of copper per kilowatt delivered. 1,000 K. W. $\times$ 57 = 57,000. If copper costs 15c. a pound the cost will be 57,000 $\times$ \$0.15 = \$8,550. Ans.

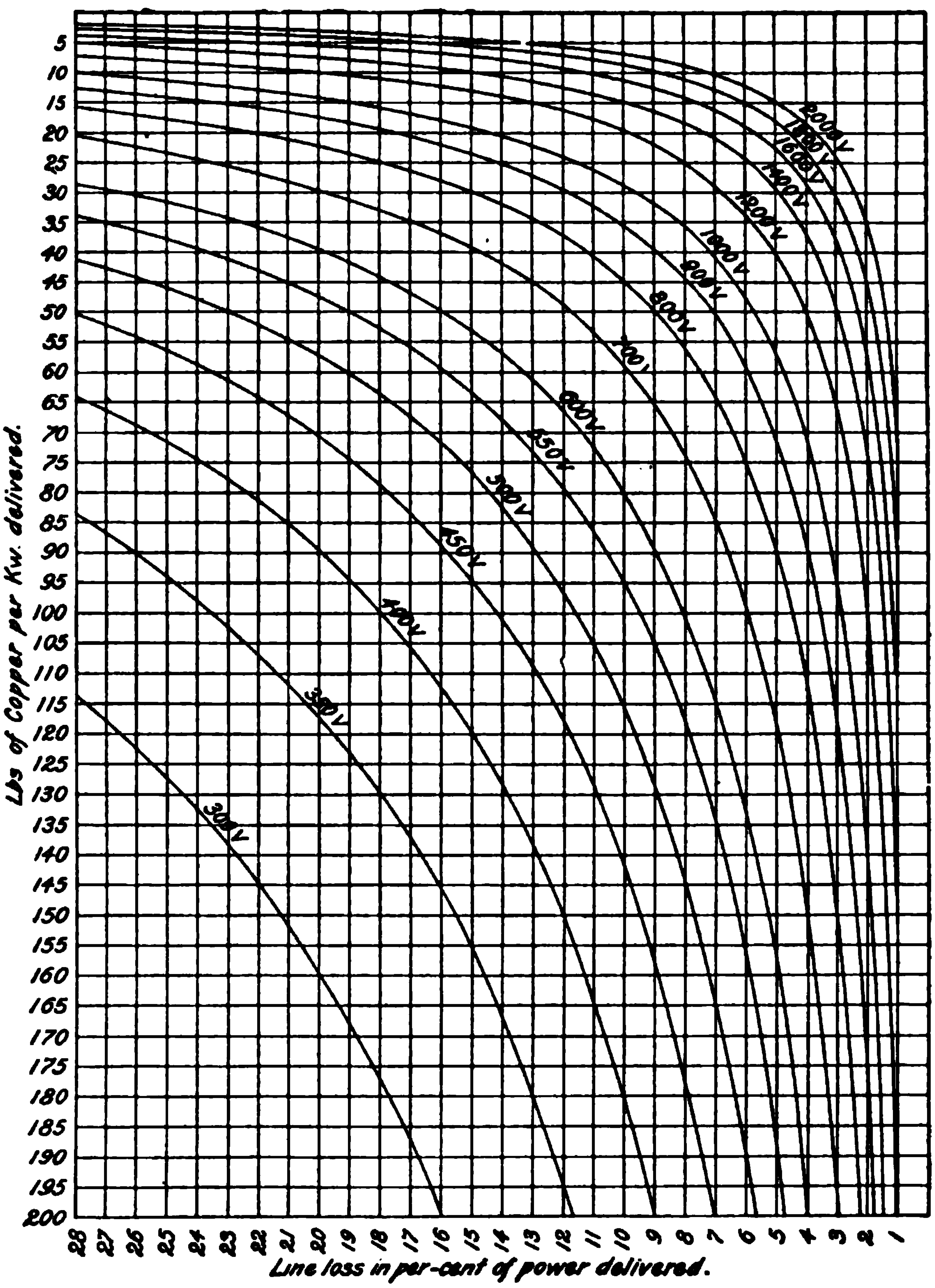

Lbs of Copper per Kw. delivered.
Line loss in per-cent of power delivered.
2000 V
1800 V
1600 V
1400 V
1200 V
1000 V
900 V
800 V
700 V
600 V
550 V
500 V
450 V
400 V
350 V
300 V
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FIG. 12

COMBINED OPERATION OF DIRECT-CURRENT DYNAMOS

OPERATION OF DYNAMOS IN SERIES

56. Dynamos are not very often run in series. Perhaps the most common case is where they are run in pairs of two in series on the three-wire system. Whenever dynamos are connected in series, their pressures are added in the same way as the voltage of two or more cells connected in series, but the current output is not increased. Series-wound dynamos are sometimes run in series, especially when used for arc lighting. In this case, the connections are very simple; the positive pole of one machine is connected with the negative pole of the other, so that the pressures of the two machines are added together instead of opposing each other. Generally speaking, series-wound, shunt-wound, or compound-wound machines may be run in series with very little difficulty; in the case of the last named type, the compound coils must of course be connected in series in the line. In most cases, however, the demand is for a large current output rather than for a high voltage; hence, plain series running is not common, except, perhaps, on arc-light circuits.

OPERATION OF DIRECT-CURRENT DYNAMOS IN PARALLEL

57. Dynamos, both direct and alternating, are much more frequently operated in parallel than in series. In Fig. 13 each machine generates the same voltage, and the pressure between the lines is the same as if a single machine were used; i. e., the pressure between the lines is not increased by adding machines in parallel, but the current delivered to the line is increased because the line current is the sum of the currents delivered by each of the machines.

Each machine is connected through its main switch M, M' to the heavy conductors C, D, like terminals of each machine being connected to the same bar. Each machine, when so connected, delivers current to the main **bus-bars** C, D and thence to the line.

It is not as easy a matter to operate machines in parallel as in series. It is evident that the voltage of each of the machines must be kept at the proper amount if the combination is to operate satisfactorily; for, suppose the E. M. F. of B should fall below that of A, then A would send current through B and run it as a motor, and B would thus be

FIG. 13

taking current from A instead of helping it feed into the line. There are a number of things that must be taken into account when machines are run in parallel that do not have to be considered when they are run separately. Compound-wound machines are run in parallel more than any other type in this country, though shunt machines are frequently run in this way also. Series machines are seldom run in parallel, for reasons to be given later. We will, however, first consider the series machine briefly, because the compound-wound machine is a combination of the series- and shunt-wound machines.

SERIES DYNAMOS IN PARALLEL

58. Suppose two series dynamos are in parallel, as shown in Fig. 14, and assume that they are delivering current to a load of some kind and that each machine supplies, say, one-half of the current. Now, if the E. M. F. of one of the machines *A* drops slightly, due to a slight variation in speed or any other cause, the amount of current delivered by *A* will decrease, and thus decrease the field excitation, because the current through the field coil is the same as the current delivered by *A*. This lowering of the field excitation of *A* will still further cut down its E. M. F. and matters will go from bad to worse until, in a very short time, *A* will be driven as a motor, unless the belt on the heavily loaded machine should slip and thus bring down its voltage. The trouble is

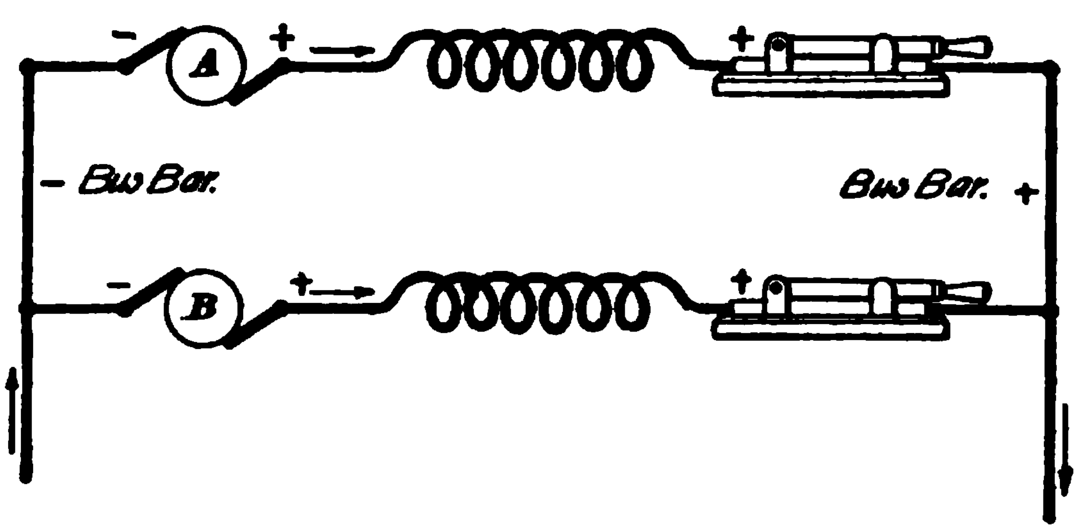


Fig. 14

made still worse by the fact that the extra load thrown on *B* will raise its E. M. F., because the field of *B* will be strengthened. Moreover, when *A* is run as a motor, its direction of rotation will be reversed; and this may result in considerable damage. It is thus seen that two series machines connected in parallel, as shown in Fig. 14, will be very unstable in their action, and it is not practicable to so operate them.

59. Equalizing Connection.—The unstable condition just referred to can be remedied by using an equalizing connection, or **equalizer,** as it is commonly called. This is shown in Fig. 15, where the wire *c d* is the equalizer. It is a wire of low resistance connecting the points *c* and *d*

where the series-coils are attached to the brushes; *e* and *f* are the regular terminals of the machine. Now suppose that the machine *B* delivers a greater current than *A*; part of this current will flow to the + line through the coil *df*, but part of it will also take the path *d–c–e* through the field coil *ce* of

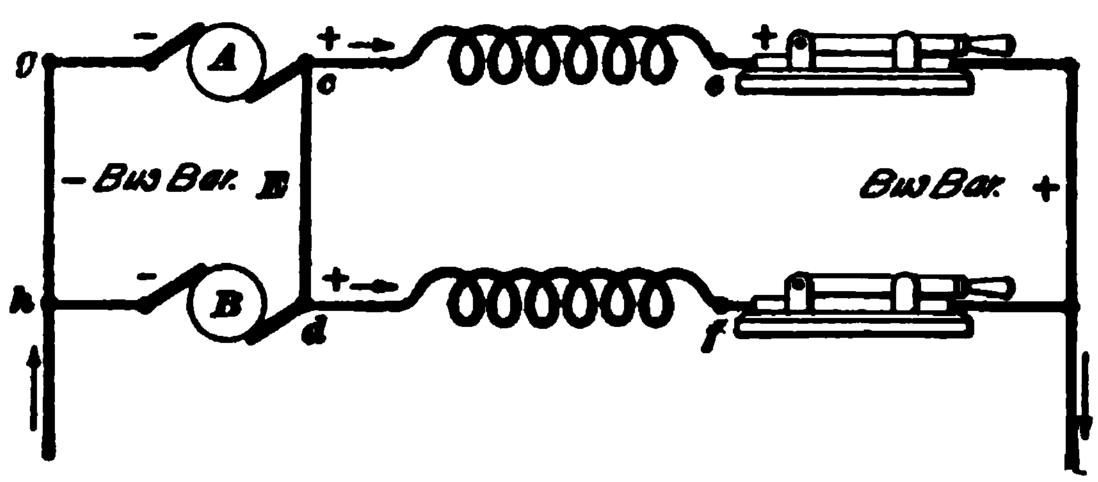


FIG. 15

machine *A*. The result is that part of the current delivered by *B* helps to keep up the field excitation of *A*, thus bringing up its voltage and equalizing the load between the machines. If *A* delivers the greater part of the load, due to a drop in the voltage of *B*, then part of the current flows through the path *c–d–f* and strengthens the field of *B*.

SHUNT DYNAMOS IN PARALLEL

60. Shunt dynamos will operate very well in parallel. They have two properties that make their parallel operation a comparatively easy matter. In the first place, they are capable of exciting their own field no matter whether they are delivering current to the main circuit or not. In the second place, their voltage drops slightly with an increase in the load, and this tends to make their parallel operation stable. Suppose two shunt machines are arranged as shown in Fig. 16; *A* and *B* are the armatures, *S*, *S'* the shunt field windings, and *r*, *r'* the adjustable field rheostats. *L*, *L'* are switches in the field circuit and *M*, *M'* main switches connecting the machines to the line. Suppose that machine *A* is in operation, as indicated by the closed position of switches *L* and *M*. To throw machine *B* in parallel, it is run up to speed and the switch *L'* closed; *B* will at once

begin to pick up its field and run up to voltage. If the two machines are generating the same voltage and if their polarity is the same, as it should be, a voltmeter connected to blocks *1*, *2* will give no deflection, because the tendency of the machine *A* to send current through the voltmeter will be opposed by *B*. This state of affairs can be brought about by adjusting the rheostat r' until the voltmeter indicates that the voltages of the machines are equal, after which the switch M' may be closed and the field excitation of *B* again adjusted until the proper share of the load is carried. In practice, it is generally found better to have the voltage of *B* about 1 or 2 per cent. higher than that of *A* when the machine is thrown in.

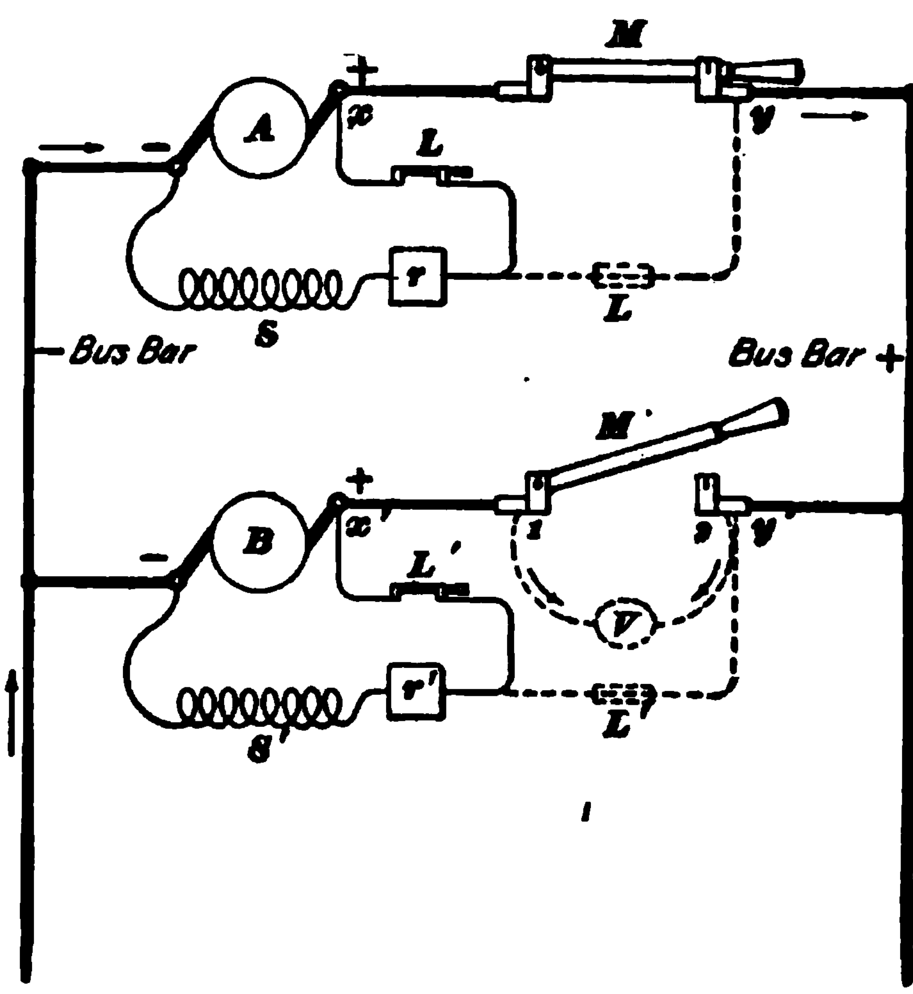


FIG. 16

Very often, when shunt machines are arranged for parallel operation, the field is connected across the bus-bars instead of the armature of each machine. When this is the case, the field connection is made as indicated by the dotted lines $r y$, $r' y'$, instead of being connected as shown by the full lines $r x$, $r' x'$. The effect of this is that the switch *M* must be closed before *A* will pick up, assuming that *B* is not in operation. If *A* is running and *B* is to be thrown in, then the switch L' is closed and *B*'s field is at once excited from the mains, so that *B* comes up to voltage almost immediately; after the voltage has been adjusted, switch M' may be thrown in as before.

61. We will suppose that the two shunt machines, Fig. 16, are running properly in multiple and will now see whether

their operation will be stable or not. It has already been seen that the shunt dynamo lowers its voltage as the current output increases. Now suppose that the voltage of *A* should drop slightly on account of a drop in speed or from any other cause. The tendency will be to throw the bulk of the load on *B*, with the result that *B*'s voltage will also drop on account of the above-mentioned property. The dropping of *B*'s voltage will relieve it of part of its load and will make it divide with *A*. It is thus seen that there is an automatic tendency for the load to equalize. Again, suppose that the load on the line is suddenly increased, and that machine *B* takes more than its share of the current; the large current delivered by *B* will cause its E. M. F. to drop to more nearly that of *A*, and the load will thus be equalized. If the voltage of one machine should for any reason become so low that the other machine runs it as a motor, no harm is liable to result, because the direction of rotation of the machine as a motor will be the same as when driven by the engine as a dynamo. As far as parallel running goes, the shunt dynamo is satisfactory, but it has been replaced by the compound machine, because the latter will maintain the line voltage with an increase of load; whereas, with shunt machines, the line voltage will fall off, unless the switchboard attendant cuts out some field resistance.

COMPOUND MACHINES IN PARALLEL

62. Since the compound machine is a combination of the series and shunt machines, one would naturally infer that the arrangement for parallel running would be a combination of the two preceding ones. Fig. 17 shows the connections in their simplest possible form; machines *A* and *B* are of equal size and the equalizer *E* runs directly between them; *c* and *f* are the + terminals of the machines, while *c d* and *f e* represent the leads, or cables, running to the switchboard; *g h* and *k l* are the negative leads running to the negative bus-bar *h l*. There would, in practice, be a main switch in each of these negative leads, but as they

are not essential for the present purpose they have been omitted. As shown by the full lines in Fig. 17, the shunt windings of the machines are connected in what is known as **short shunt**; i. e., the shunt field is connected across the brushes. Sometimes the shunt field is connected in **long shunt** across the terminals of the machine or across the bus-bars. It makes very little difference as to the performance of the machine which connection is used.

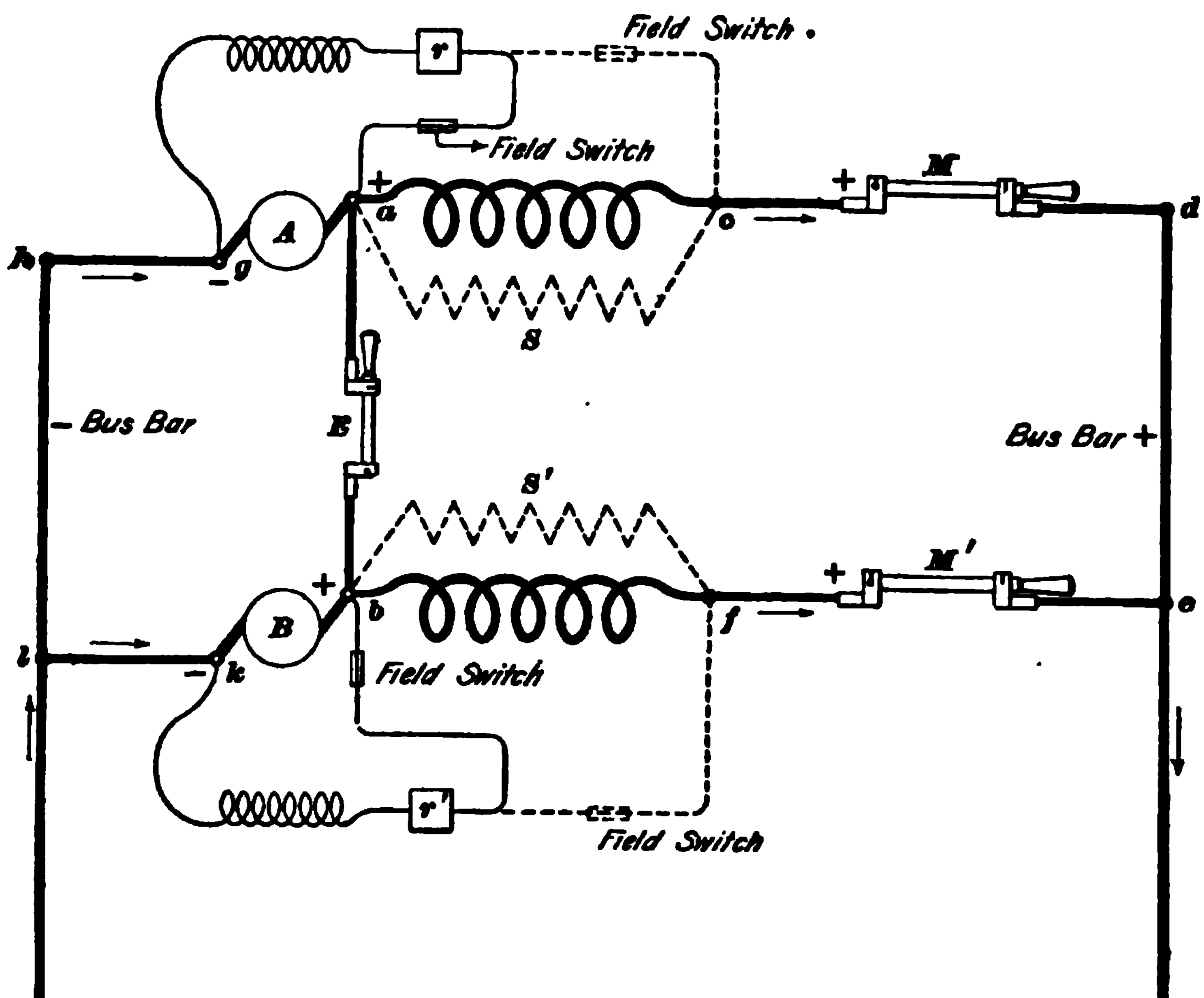


Fig. 17

Most compound machines are provided with low-resistance shunts S, S' across their series-coils in order that the degree of compounding may be adjusted. These shunts should be adjusted so that the machines, when running separately, will give the same degree of compounding, which means, in the present case, that when each machine is delivering the same current, the voltage generated will be the same, because we are now assuming that A and B are of equal

size. Another condition that must be fulfilled is that the resistance between the points *a* and *d* must be the same as between *b* and *e*. Since we are, for the present, assuming that the machines are of the same size and make, the resistance of their series-coils *a c* and *b f* will be almost exactly the same. The resistances of the switchboard leads *c d* and *f e* must, therefore, be equal; the resistance of the equalizer *E* should be as low as possible, and it should never be more than the leads *c d* or *f e*.

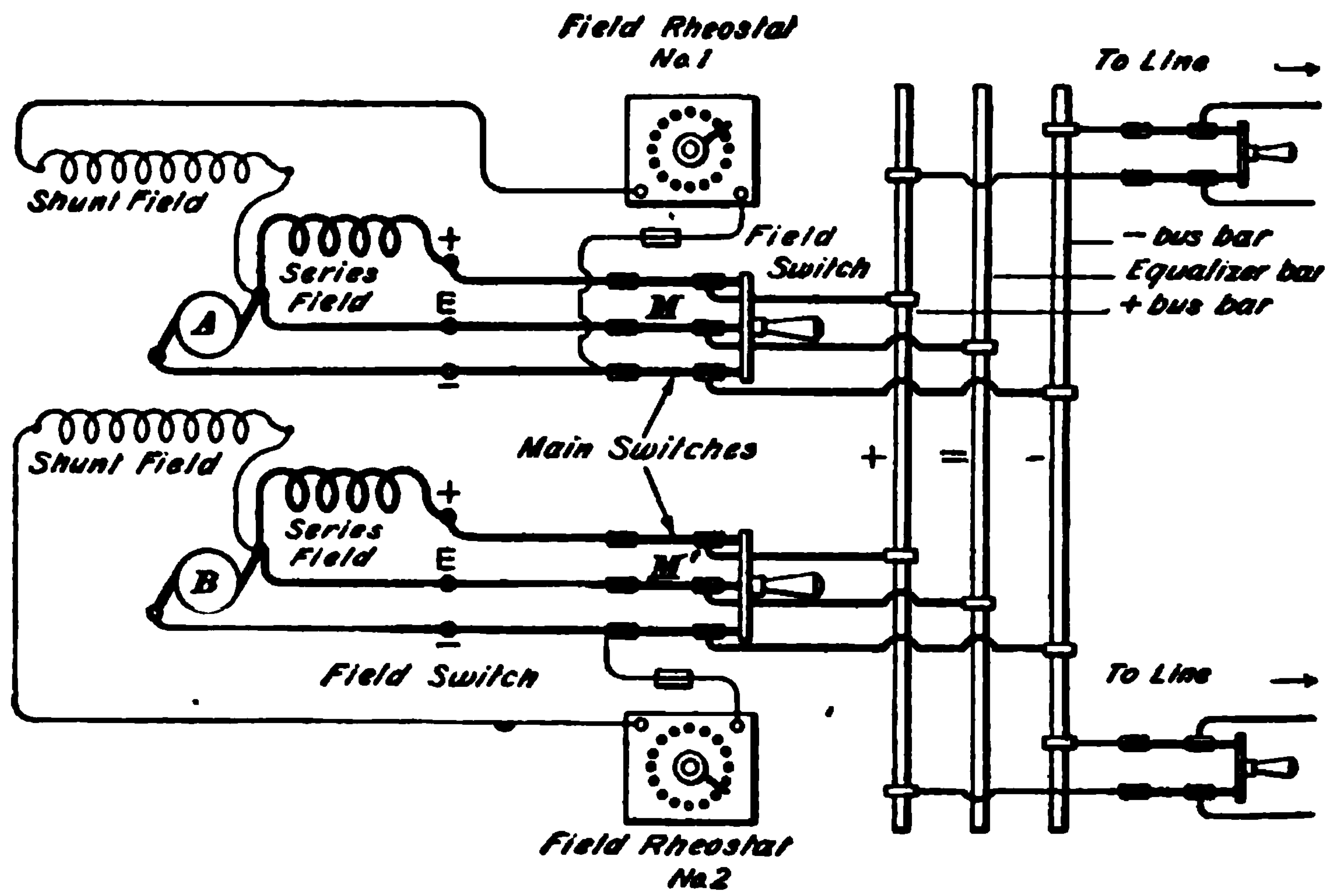


Fig. 18

63. We will now examine the action of the machines under a varying load. In the first place, if the resistance between *a d* is equal to that between *b e* and the machines are delivering equal currents, then the drop through *a d* will equal the drop through *b e* and points *a* and *b* will be at the same potential. Since current can only flow between points at different potentials, there will be no current in *E* under such circumstances. Suppose, however, that *A* delivers a greater current than *B*; then the drop in *a d* will exceed that in *b e* and current will flow through the path *a–E–b–f–M'–e* and thus build up the voltage of machine *B* and equalize the load. If *B* delivers more current than *A*, the drop in *b e*

exceeds that in *a d* and current flows through the path *b–E–a–c–M–d*, builds up the voltage of *A*, and makes *A* take its share of the load.

64. In Fig. 17 the equalizer *E* is shown as connecting the positive brushes. This is usually the case in practice, though it would work just as well if both *a* and *b* were negative brushes and *c f* the negative terminals of the machines. It is only necessary to see that the equalizer connects those brushes to which the series-coils are attached, and also to see that the brushes are of the same polarity on each of the

FIG. 19

machines. In some cases, the equalizer wire is run directly between the machines as shown, but often a third wire is run from points *a* and *b* to the switchboard and there connected to an equalizer bar, as shown in Fig. 18. This represents a very common arrangement, triple-pole switches being used; the two outside blades for the + and – leads and the middle blade for the equalizer. There is a difference of opinion as to whether it is better to run the equalizer to the switchboard or run it directly between the machines, as in Fig. 17. The most recent practice tends toward running it directly and placing the equalizer switch near the machine.

This undoubtedly makes the connections shorter and thus leads to better regulation. In such cases, the equalizer switch is usually mounted on a pedestal near the machine, as shown in Fig. 19.

65. In some railway plants, especially in those where large generators are used, the main switch that is on the same side of the machine as the equalizer is placed on the stand near the machine alongside the equalizer switch. These two

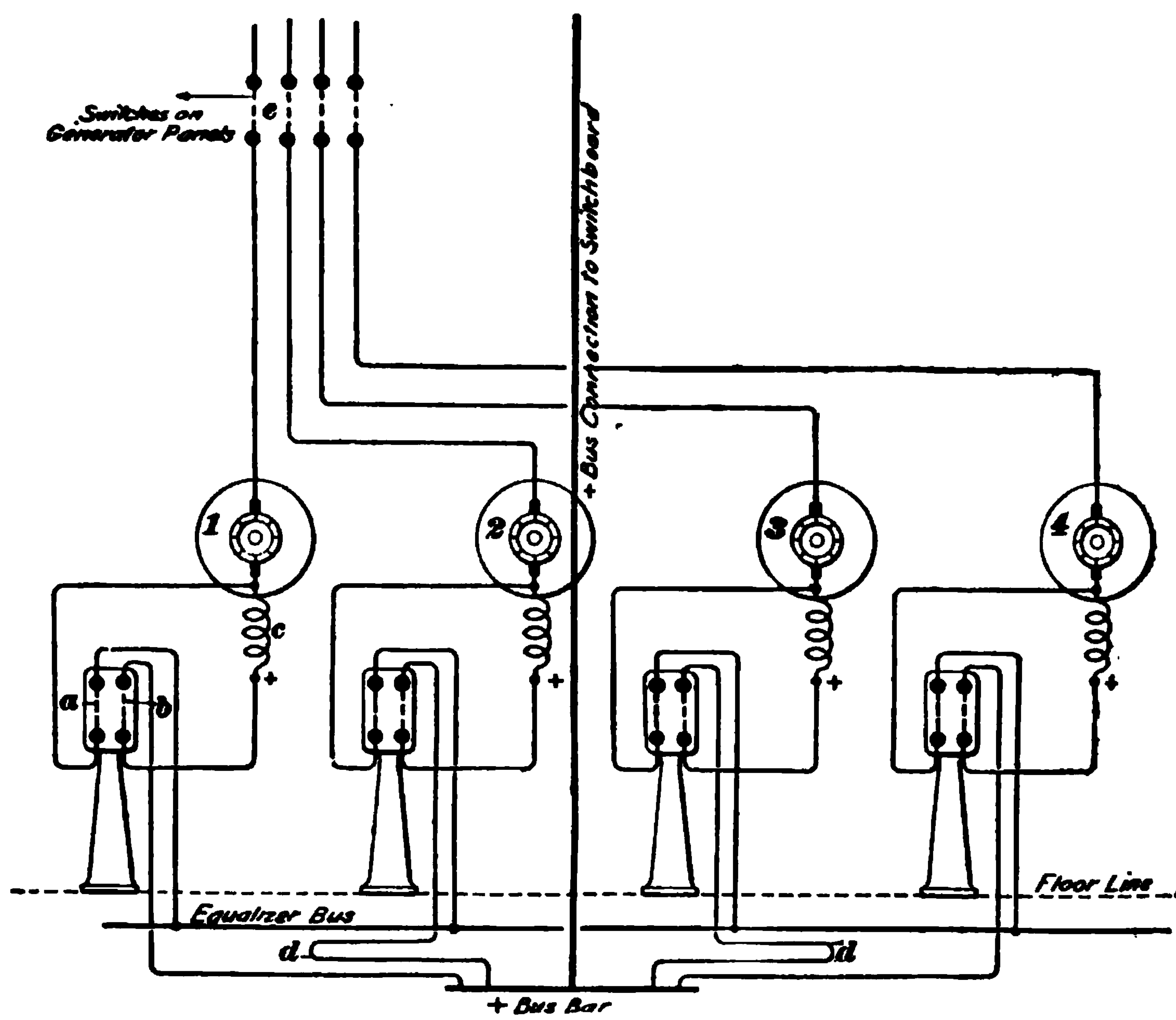


FIG. 20

switches are at practically the same potential, and there is no objection to placing them near each other. In case this is done, one of the bus-bars is placed under the floor near the machines and connected directly to the main switch. This shortens the connections considerably and makes the equalization of the load closer. It also has the advantage of simplifying the switchboard connections and avoiding crowding on the generator switchboard panels. Fig. 20

shows the arrangement referred to. For lighting switchboards or for small railway boards, both terminals of each machine are run to the switchboard. In Fig. 20 the main connections only have been shown, the shunt coils of the machines and all minor connections being omitted. The switches *a* and *b* are the equalizer and main + switches, respectively, the equalizer switch being connected to the brush to which the series-field *c* is attached. The + lead from *b* connects to the + bus-bar under the floor. Note that these leads should all be of the same length in order to secure close equalization. In the case of machines *2* and *3* the leads are doubled back as shown at *d* in order to make them of the same length as those running from the more distant machines.

The general method of starting up, say, machine *1* and throwing it in parallel with others is as follows: See that all switches on the generator panel of the machine are open, and get the dynamo up to speed. Then close the equalizer switch *a* and the + switch *b*. Also, close the field switch on the generator panel. Some of the current furnished by the other machines will flow through the series-coils *c*, because the series-coil of machine *1* is in parallel with the other series-coils. This current in the series-coils will cause the machine to *pick up* rapidly, and since the shunt circuit is also closed, the machine soon comes up to full voltage. The voltage is then adjusted by means of the rheostat until it is equal to or a little higher than that of the other machines, and the negative switch *e* is then closed, thus placing the machine in parallel with the others. This method of procedure applies to the case where the +, −, and equalizer switches are independent of each other, as is usually the case in modern installations. When triple-pole switches are used, as in Fig. 18, all three must of course be closed together after the machine has been allowed to pick up its field and has had its voltage adjusted. After the machine has been thrown in parallel, its load is adjusted by varying the field excitation. In case the machine is provided with a circuit-breaker, as is nearly always the case on modern switchboards, the circuit-breaker should be closed before the

main switch. If any rush of current then occurs when the main switch is closed, the circuit-breaker is free to act and disconnect the machine.

66. Main and Equalizer Cables.—In connecting the machines to the switchboard, cables of ample capacity should be used. For most cases it will be sufficient to allow from 1,200 to 1,500 circular mils per ampere. For very large currents it is advisable to use two or three cables in parallel rather than a single large cable, as better radiating facilities are thereby provided. The equalizer should be of the same size as the main cables. In some cases an allowance as low as 1,000 circular mils per ampere is made for these main cables, but the better practice is in favor of a more liberal cross-section.

67. So far, in all that has been said, the machines were supposed to be alike in size and general design. Under such circumstances, there is generally no great difficulty in getting compound machines to operate properly in parallel. Trouble is often experienced, however, when it comes to operating machines of different construction and size. Some field magnets will respond to changes in field excitation much more quickly than others, and other differences in design may have considerable effect on the performance of the machines when they are run in parallel. With two machines of different size, the problem is to get the load to divide between them in proportion to their size. For example, suppose a large machine A is connected in parallel with a smaller machine B, as shown in Fig 21. Each is supposed to be adjusted so that it gives the same degree of compounding when operated by itself. Also, when each machine is delivering its proper share of the load, the drop between $a\,b$ must equal the drop between $c\,d$. For example, if I is the full-load current of A, R the resistance between a and b, I' the full-load current of B, and R' the resistance between c and d, then $I\,R$ must equal $I'\,R'$. Now, the resistance of the series-coils cannot very well be altered in order to bring about the required condition of affairs, so that the only remedy is to insert resistance of

some kind in the leads $e\,b$ or $f\,d$ until the above drops become equal. This resistance will, of course, be very small and may be made up of a short piece of heavy German-silver strip or even an extra amount of cable in one of the leads. In the figure, it is indicated at x, though it may be necessary to insert it in the main lead of machine B. The resistance must be inserted in series with the machine giving the least drop between the points mentioned above. Many times the attempt is made to bring about the adjustment by changing

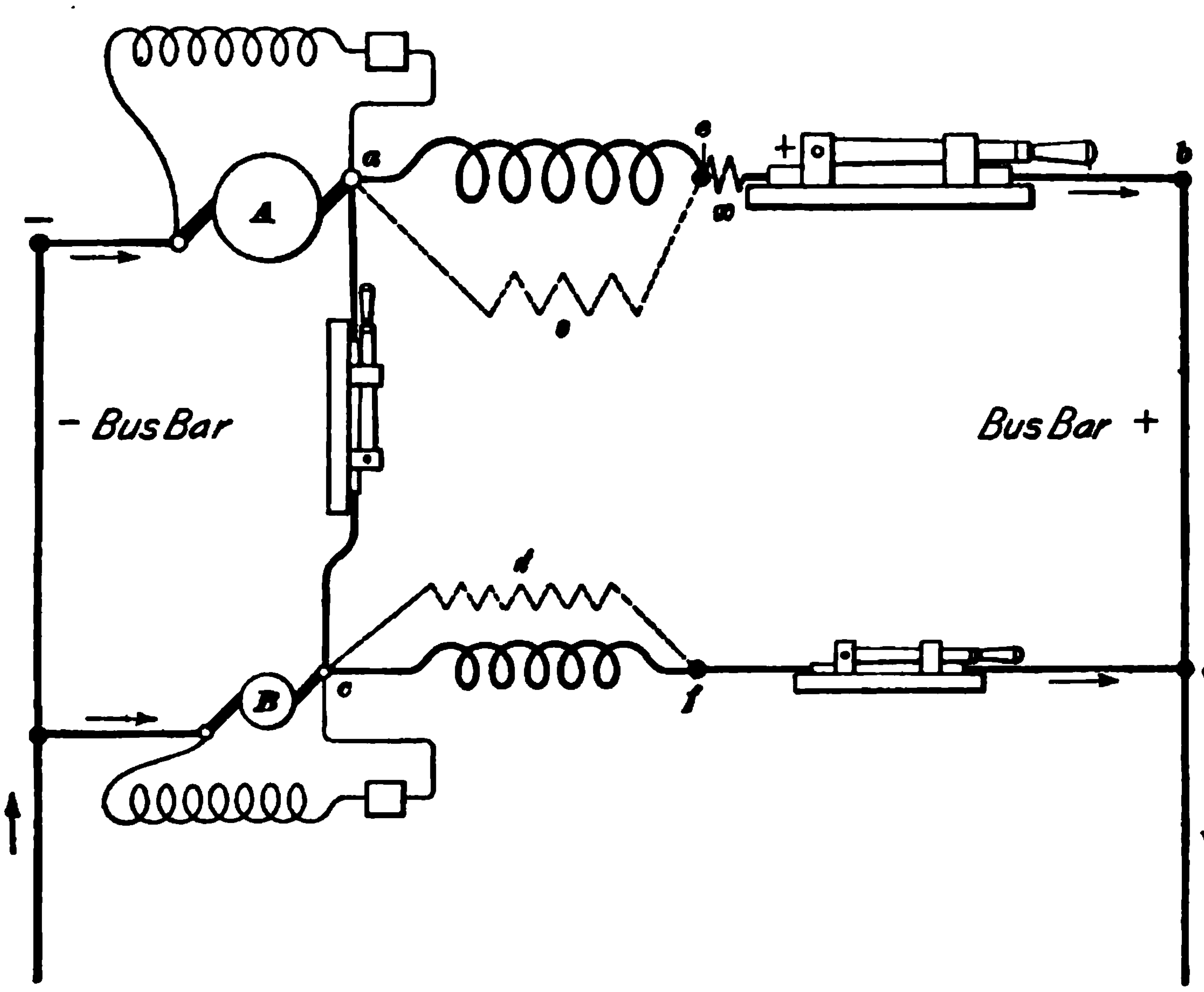


Fig. 21

the shunts s, s', but such attempts are useless, because just as soon as the machines are put in parallel, s and s' are also in parallel and are practically equivalent to one large shunt across the fields of both machines. The consequence is that any change in the shunts affects both machines. The adjustment must, therefore, be made in the main lead between the series-coil and the bus-bar, and any resistance so inserted must have the same carrying capacity as the series-coils. A change in the shunt across the series-coils will change the

compounding of the machines as a whole, but it will not better their condition as regards the correct division of the load.

68. Compound Machines in Parallel With Shunt Machines.—It is not practicable to run a compound machine in parallel with a shunt machine. If, for any reason, the compound machine takes a little more than its share of the load, the strengthening of its series-coils makes it still further overload itself, with the result that the field rheostat of the shunt machine calls for constant attention. The only way to run this combination satisfactorily is either to cut out the series-coils of the compound machine, thereby making both plain shunt machines, or else provide the shunt machine with compound coils.

COMBINED RUNNING OF ALTERNATORS

ALTERNATORS IN SERIES

69. Alternators cannot be run in series unless their armatures are rigidly connected by being mounted on the same shaft, so that the E. M. F.'s generated by the two machines will always preserve exactly the same relation with regard to each other. If the machines are driven separately, the E. M. F.'s may aid each other at one instant and oppose each other the next, thus making their operation unstable. There is, in any event, little occasion for operating alternators in series; the object of series operation is usually to obtain a high voltage, and this can readily be generated in a single alternator, or, if the alternator does not furnish a sufficiently high voltage, the pressure can easily be raised by means of transformers.

ALTERNATORS IN PARALLEL

70. Alternators can be operated in parallel, although they are, as a rule, more troublesome than direct-current machines. This is especially the case if they are very different in size and design. For example, alternators with the old-style, smooth-core armatures are hard to run in parallel

with modern machines having toothed armatures. In fact, in many of the older lighting stations special precautions were taken at the switchboard to see that two alternators should never be thrown in parallel.

71. Alternators are operated in parallel in much the same way as direct-current machines, so far as connections are concerned; i. e., they are usually connected to bus-bars through the intervening main switches. If the alternators are compound wound, equalizing connections should be used;

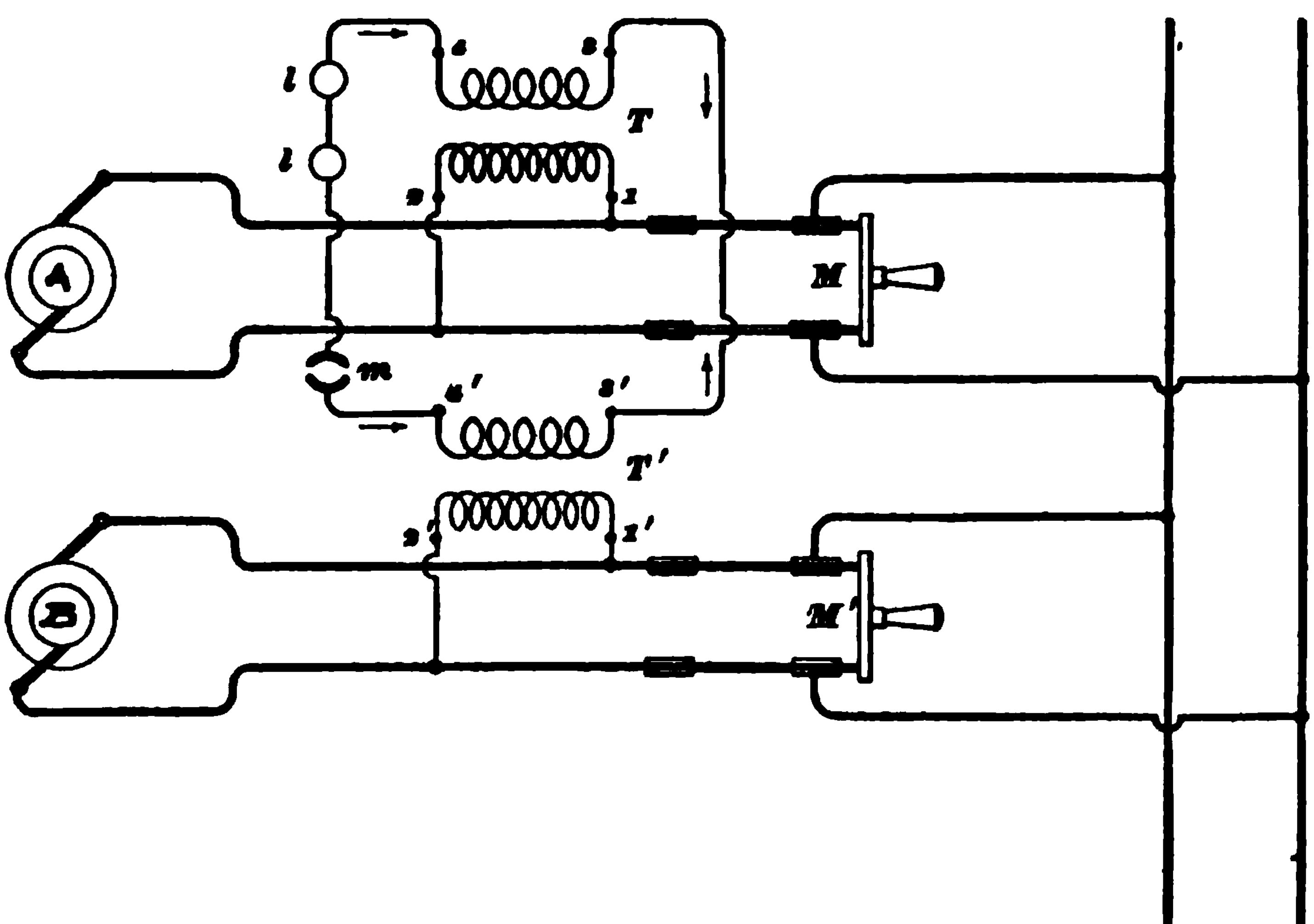


FIG. 22

but very many are operated with a separately excited field only and no equalizing connection is necessary, the whole scheme of connection corresponding more nearly to the running of shunt-wound machines in parallel.

Suppose two single-phase alternators *A* and *B* are connected in parallel. In order that the machines may operate properly and each take its proper share of the load, it is, of course, necessary to have their voltages equal or nearly so. There is another important condition that must also be fulfilled; the machines must be in **synchronism.** This

means that both machines must run at exactly the same frequency, for if this were not the case, they would get out of step. Before two alternators are thrown in parallel, equality of frequency is the most important condition to be fulfilled. A slight difference in phase will cause an exchange of current between the machines, but they will pull each other into phase if the frequencies are equal.

72. Synchronizing.—The state of synchronism may be ascertained by means of **synchronizing lamps** connected as shown in Fig. 22. T, T' are two small transformers having their primary coils connected to the alternators, as shown. It should be noted that similar terminals *1*, *1'* are connected to similar sides of the machines. The secondaries are connected in series through a pair of lamps l, l and a plug switch m. If the machines are exactly in phase, terminals *3* and *3'* will have the same polarity at the same instant and the polarities of *4* and *4'* will also be alike. But since like terminals are connected together, the two secondary voltages will just neutralize each other, as indicated by the arrows, and the lamps will not glow. If the machines were directly opposite in phase, the lamps would light up to full candlepower. It is evident that by reversing the connections of one of the transformers the state of synchronism will be indicated by the lamps being bright. When machine B is started and the plug inserted at m, the lamps rapidly fluctuate in brightness; but as B comes more nearly in synchronism the fluctuations become much slower. When they have become as slow as one in 2 or 3 seconds, the main switch M' is thrown in at the middle of one of the beats when the lamps are dark. In some cases, the connections are so made that the lamps are bright when synchronism is attained. Whether the state of synchronism will be indicated by light or dark lamps depends simply on whether the transformer secondaries are connected so as to assist or to oppose each other.

73. Synchronizing Two-Phase and Three-Phase Machines.—Fig. 22 shows the synchronizing arrangement for a single-phase machine. For a two-phase or three-phase

machine the same arrangement may be used, but care must be taken to make sure that the transformers T, T' are connected to corresponding phases on each of the machines. This may be determined by using two pairs of transformers; i. e., one regular pair, as in Fig. 22, and a temporary pair on one of the other phases. For example, on a two-phase machine an arrangement similar to that shown in Fig. 22 should be made for each of the phases, and when the connections are right, each set of phase lamps will light or

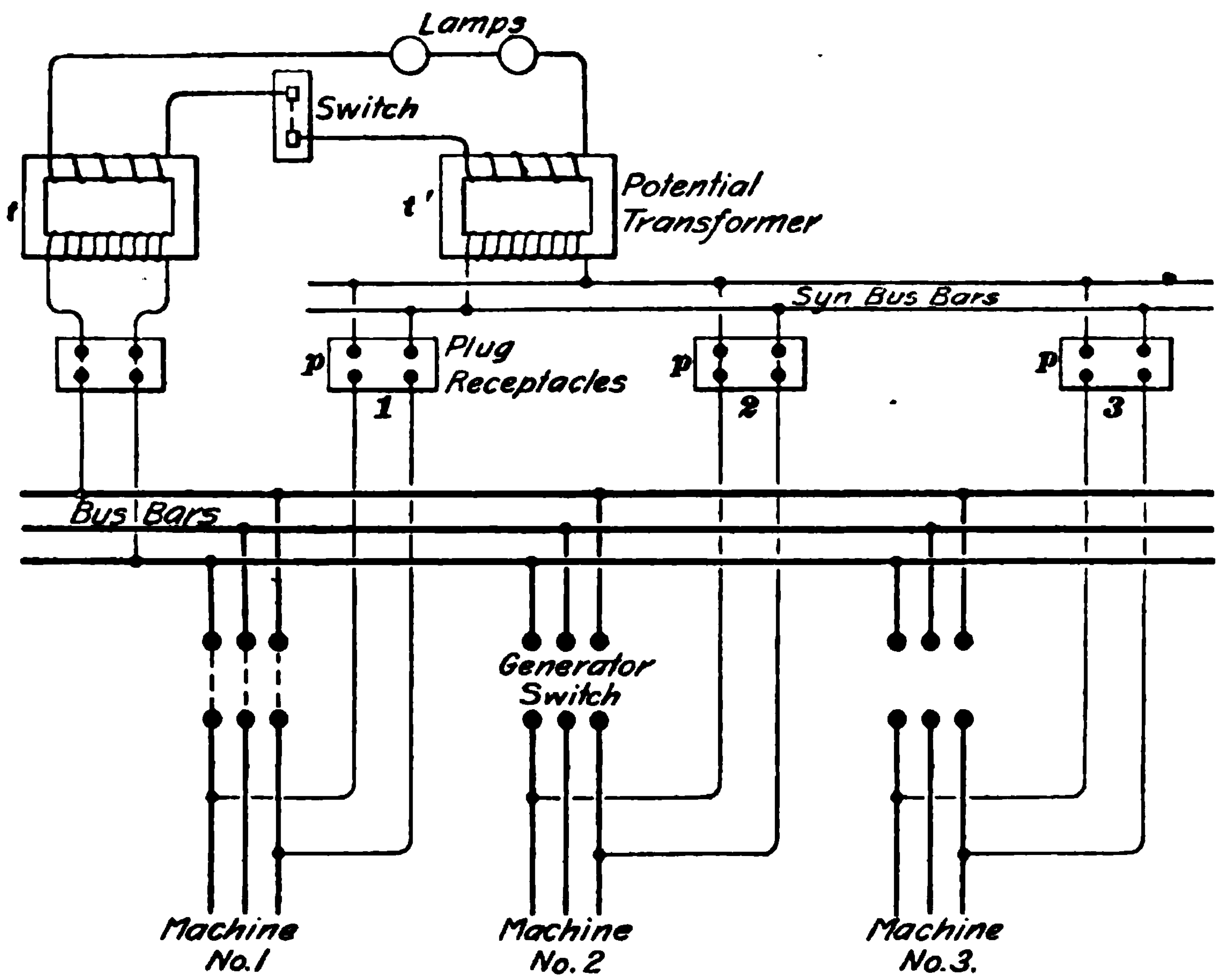


FIG. 23

become dark, as the case may be, at the same instant, showing that both phases are ready for parallel operation. After it is known that the connections are all right, the temporary pair of transformers may be removed and only one pair used, as in Fig. 22.

74. Fig. 23 shows a common scheme of connections used for synchronizing with lamps. In this case the connections are shown for three machines, each machine being provided

with its plug receptacle *p*. One small transformer *t* is connected across the bus-bars, and the other *t'* can be connected to any one of the machines by inserting the plug in its receptacle. For example, suppose the main switch of machine No. 1 is closed, as indicated by the dotted lines, and that it is desired to operate machine No. 2 in parallel with No. 1. Machine No. 2 would be brought up to speed and the plug inserted at receptacle *2*, thus connecting *t'* to the machine. With the connections as shown, synchronism is indicated when the lamps burn to full brightness, hence the generator switch of machine No. 2 would be thrown in when the lamps are at the middle of a beat and at full brightness. The same arrangement could be used for synchronizing with dark lamps, the only change being that the synchronizing plug would be cross-connected, thus making the transformers oppose each other. Should the alternators generate a low voltage, as is sometimes the case when they are used in connection with step-up transformers or for low-voltage work, it is not necessary to use transformers *t*, *t'*. All that is necessary in such cases is to connect the terminals of the synchronizing circuit direct to the machines or bus-bars and insert a sufficient number of lamps in series to stand the maximum voltage applied to them. Another plan in low-voltage work is to use autotransformers that step down the voltage to an amount suitable for the lamps.

75. Use of Voltmeter for Synchronizing.—As explained above, lamps have been used very largely in the past for indicating synchronism, but they are not entirely satisfactory for this purpose. Lamps do not indicate the point of synchronism as closely as desirable, especially when large generating units are involved, and they do not give any accurate idea as to how much the machine being synchronized is out of phase or whether it is coming into or going out of phase. If a large machine is connected to the bus-bars when out of phase, even by a slight amount, a heavy cross-current will flow, and this frequently results in burned switch contacts, to say nothing of possible worse

results. A number of schemes have been adopted for indicating the point of synchronism more exactly than is possible with lamps. Fig. 24 shows an arrangement of connections by which the machine voltmeters are used. If a voltmeter is connected in the same way as synchronizing lamps, the pressure applied to it at synchronism will be either zero or double the ordinary pressure, depending on how the transformers are connected. This would make

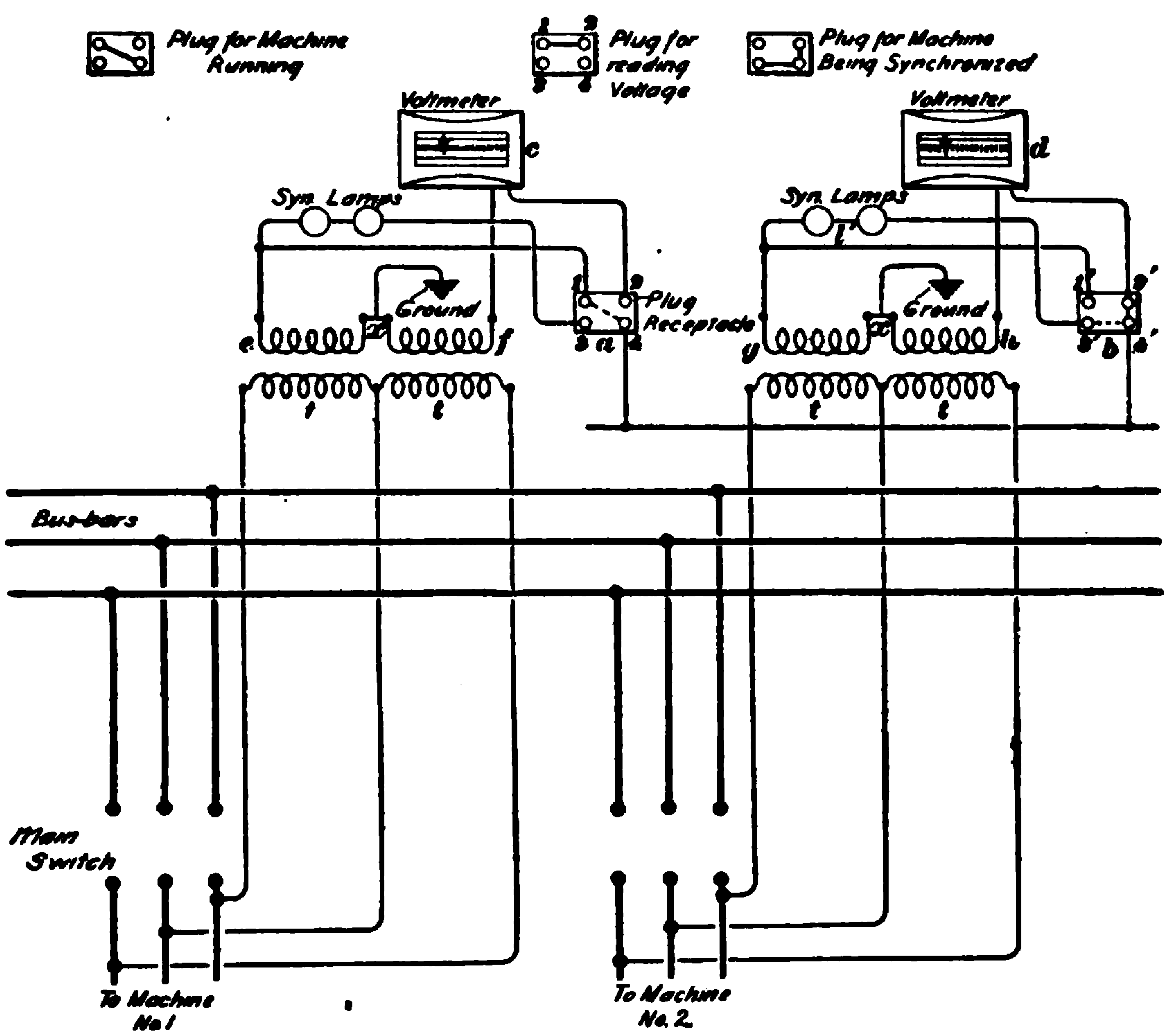


FIG. 24

the point of synchronism, as indicated by the instrument, come either at the zero end of the scale where considerable changes in voltage might make very little change in the reading, or at the maximum point of the swing where a considerable change in phase difference is necessary to cause an appreciable change in the resultant voltage. A scheme for three-phase systems, devised by Mr. J. E. Woodbridge, and shown in Fig. 24, overcomes these objections by

making the voltage applied to the voltmeter at synchronism the resultant of two E. M. F.'s differing in phase by 60° instead of two that are in phase or 180° out of phase, as is ordinarily the case. The two transformer secondaries, connected in series through the voltmeter by means of the synchronizing plug, are attached to two different phases of the three-phase system in such a way that their E. M. F.'s differ in phase by 60°. Thus the resultant E. M. F. applied to the voltmeter is, when the machines are in phase, equal to the normal E. M. F., thus bringing the pointer somewhere near the mid-point of the scale. The rate of change of the resultant E. M. F. due to changes of phase relation is also high with this connection, thus giving a more accurate indication of the exact instant at which the machines are in phase.

In Fig. 24 the connections are shown for a pair of high-pressure alternators, and two potential transformers *t*, *t* are provided for each machine. The junction of the two transformer secondaries is grounded, as shown; this not only simplifies the connections by making the ground serve as one synchronizing bus, but, what is of more importance, it precludes the existence of a high pressure between the switchboard instruments and the ground in case the insulation between primary and secondary should break down. By using suitable plugs in the receptacles *a*, *b*, the voltmeter can be used either to indicate the voltage of the machine, or for synchronizing purposes; lamps are also provided, as shown, to indicate synchronism along with the voltmeter. The plug for the machine that is already in operation connects points *1* and *4*, as shown at *a*, and the plug for the machine being synchronized connects points *2'*, *4'*, *3'*, as shown at *b*. This connects voltmeter *d* in series (by way of the ground connections) with coils *e* and *h*, and the lamps in series with coils *e* and *g*. The E. M. F.'s of *e* and *h* differ in phase by 120°, but the coils are connected in opposition so that one E. M. F. is reversed with respect to the other and the two E. M. F.'s which combine to act on the voltmeter differ in phase by 60°, as previously mentioned.

The E. M. F.'s of *e* and *g* are in phase so that the voltmeter will indicate normal voltage, and the lamps *l'* will be dark at synchronism. When the voltmeter is to be used in the regular way to indicate the machine voltage, a plug is inserted that connects the upper contacts *1'*, *2'*, thus connecting the voltmeter across the transformer and indicating the voltage between the outside wires.

76. Lincoln Synchronizer.—Voltmeters and other devices are used in many ways to indicate synchronism, and it is impossible to here treat all the different methods. Also, a number of synchronism indicators, or synchronoscopes, have been brought out; Fig. 25 shows one of these devised by Mr. Paul M. Lincoln. The terminals of the potential transformers are connected to the binding posts *a a*, *b b*, and when the incoming machine is in synchronism, the hand *h* remains stationary in the vertical position. If the machine that is being brought into synchronism is running too fast, the hand revolves slowly to the right; if running too slow, it moves to the left. The following description of the principle of operation of this instrument is that given by Mr. Lincoln.

Fig. 25

Suppose a stationary coil *F* has suspended within it a coil *A*, free to move about an axis in the planes of both coils and including a diameter of each. If an alternating current be passed through both coils, *A* will take up a position with its plane parallel to *F*. If, now, the currents in *A* and *F* be reversed with respect to each other, coil *A* will take up a position 180° from its former position. Reversal of the relative directions of currents in *A* and *F* is equivalent to changing their phase relation by 180°, and therefore this change of

180° in phase relation is followed by a corresponding change of 180° in their mechanical relation. Suppose, now, that instead of reversing the relative direction of currents in *A* and *F*, the change in phase relation between them be made gradually and without disturbing the current strength in either coil. It is evident that when the phase difference between *A* and *F* reaches 90°, the force between *A* and *F* will become zero, and a movable system, of which *A* may be made a part, is in condition to take up any position demanded by any other force. Let a second member of this movable system consist of coil *B*, which may be fastened rigidly to coil *A*, with its plane 90° from that of coil *A*, and with the axis of *A* passing through a diameter of *B*. Further, suppose a current to circulate through *B*, whose difference in phase relative to that in *A* is always 90°. It is evident under these conditions that when the difference in phase between *A* and *F* is 90°, the movable system will take up a position such that *B* is parallel to *F*, because the force between *A* and *F* is zero, and the force between *B* and *F* is a maximum; similarly, when the difference in phase between *B* and *F* is 90°, *A* will be parallel to *F*; that is, beginning with a phase difference between *A* and *F* of 0°, a phase change of 90° will be followed by a mechanical change in the movable system of 90°, and each successive change of 90° in phase will be followed by a corresponding mechanical change of 90°. For intermediate phase relations, it can be proved that under certain conditions the position of equilibrium assumed by the movable element will exactly represent the phase relations; that is, with proper design, the mechanical angle between the plane of *F* and that of *A*, and also between the plane of *F* and that of *B*, is always equal to the phase angle between the current flowing in *F* and the currents in *A* and *B*, respectively.

77. Fig. 26 shows the general arrangement of the instrument. As seen from the figure, the construction is similar to that of a small motor. The field *A A* is built up of iron laminations, and is wound with coils *F*, *F* that are connected

in series and joined to the secondary of the potential transformer whose primary is connected to the bus-bars. The armature core B is of the drum type, and is wound with two coils C and D that are approximately at right angles to each other. These coils are connected in series, and their junction x is connected to the middle ring 2 of three collector rings mounted on the shaft. The other two terminals are connected to rings 1 and 3. The middle ring, through its brush, connects directly to one terminal of the potential transformer of the machine to be synchronized. Ring 3 connects to a choke coil or inductance L; ring 1 connects to one terminal of a non-inductive resistance R. The remaining terminals of R and L are joined to y and connect to the other terminal of the potential transformer. The inductance L and resistance R are adjusted so that the currents in the coils C and D differ in phase by very nearly 90°. The current in the coils F, F will lag nearly 90° behind the E. M. F. E, because of the high inductance of the field coils; consequently, the magnetism set up by the field will be 90° behind the E. M. F. E. When the current in coil D is in phase with the field magnetism, D will swing around until it assumes the vertical position where its plane is at right angles to that of the field. The current in D is 90° behind E', because of the inductance L; hence, at synchronism the current in D is in phase with the field magnetism, and the pointer assumes the vertical position. The current

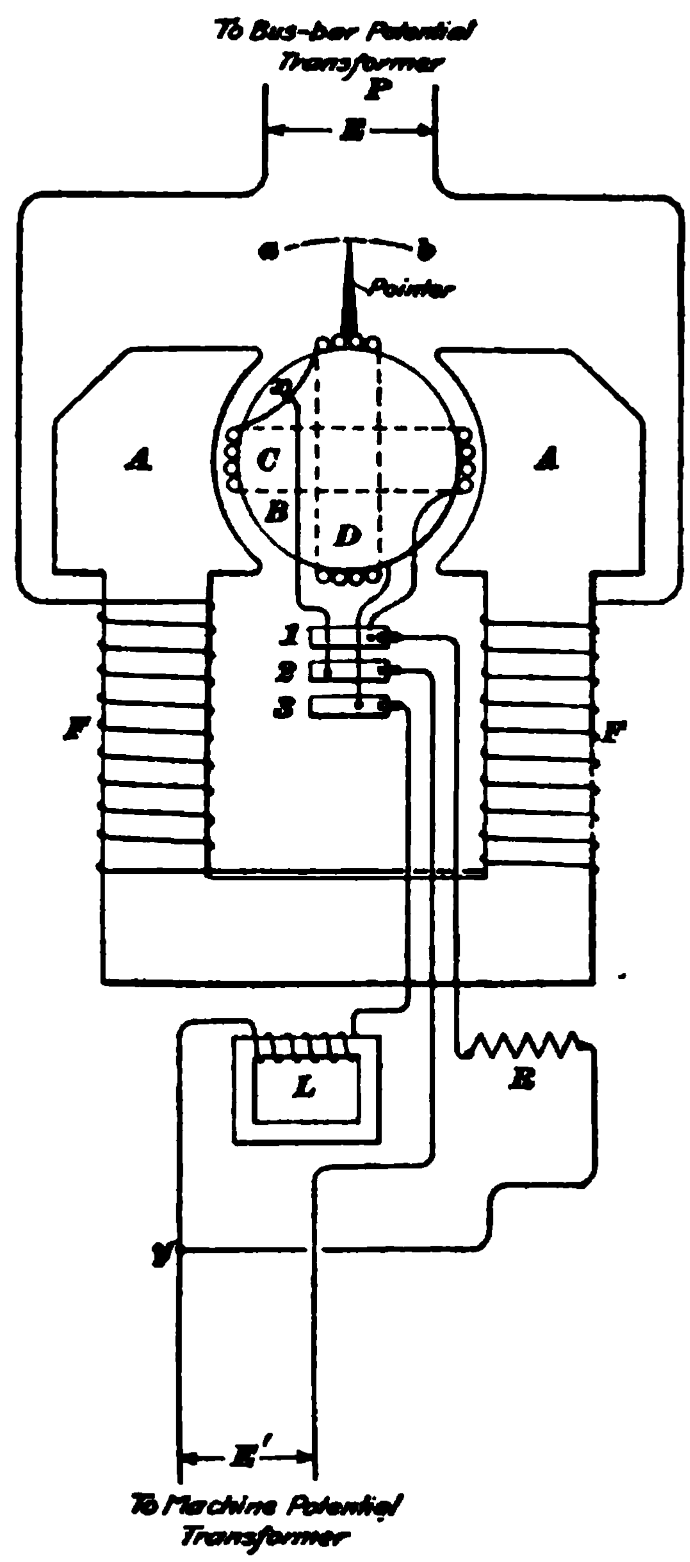


Fig. 26

in C is in phase with E', and hence differs in phase from the field current by 90°; hence, at synchronism no torque is exerted on coil C if the frequencies of E and E' are equal. But if E and E' differ in phase by 90°, then the current in D is at right angles to the field and the current in C is in phase with the field magnetism; consequently, coil C assumes the vertical position, and the hand swings around through 90°. For a phase difference of less than 90° the pointer assumes an intermediate position. If the machines do not have equal frequencies, i. e., if the machine being synchronized is running too fast or too slow, the phase difference between the field on one hand and C and D on the other is constantly changing, and, therefore, the pointer will revolve at a speed depending on the difference in speed of the alternators. From the direction of rotation, the attendant can tell at once whether the machine being synchronized requires speeding up or slowing down. The synchronizers made by the General Electric and Westinghouse companies operate on the above principle, and are now generally used instead of lamps or voltmeters.

78. The foregoing will give a general idea as to some of the methods in common use for indicating synchronism. As before stated, there are a great many possible arrangements and modifications of the connections, but the principles involved are much the same in all of them. Some devices have been proposed to make the action of synchronizing automatic; that is, to close the main switch automatically when the point of synchronism is reached instead of leaving the time of closing to the judgment of the operator. The object is to prevent the machines from being thrown together at the wrong time, and although a number of such automatic devices have been patented, they have not as yet come into general use. One arrangement for closing the switch is that patented by Mr. Lincoln in connection with the synchronizer just described. An electrical contact is arranged so that a circuit will be established when the pointer is anywhere within an arc, such as a b,

Fig. 26. This arc represents the amount of phase difference that is allowable and yet have the machines go together without making a disturbance. The current through this electric contact operates a switch or relay that in turn closes the main switch. It is necessary that the relay shall only operate when the pointer is revolving at a very low speed; or, in other words, when contact exists for a considerable time. This is accomplished by providing the relay with a dashpot that prevents it from closing unless the current through its magnet is maintained for an appreciable length of time. If this were not done, the machines would be thrown together when their frequencies were unequal, because the hand in its revolution would make contact with the arc and close the circuit. It is only when the hand is moving very slowly that the switch should be operated.

FEATURES CONNECTED WITH PARALLEL OPERATION

79. When two alternators are running in parallel, each will hold the other in step and they will each run at such a speed as to give the same frequency; if the alternators have the same number of poles, their speeds will be exactly the same. When direct-current generators are operated in parallel, they do not necessarily run at the same speed and the load carried by each machine can be varied by changing the field excitation. When the load is increased, the engine speed drops a little and the governor admits more steam to the cylinders, thus increasing the power supplied. In the case of alternators, the machines are compelled to run at the same speed, and each alternator will deliver power in proportion to the power supplied to it from its prime mover. Changing the field excitation will not change the power delivered; the only effect of changing the field strength will be to set up local currents between the machines. The field strength should be adjusted so that, for a given total current delivered, the current delivered by each machine will be a minimum; or, so that the sum of the currents as indicated by the machine ammeters will equal the total current as nearly as possible.

The problem, then, of making a proper division of the load is more difficult in the case of alternators than direct-current machines. The alternators are compelled to run at the same speed just as if they were actually geared to a common shaft, and any decrease in the speed of one must be accompanied by a corresponding decrease of speed in the other. Now, the governors of steam engines and water-wheels are designed so that a certain small decrease in speed is necessary, with increase of load, to make them operate. For example, suppose a steam engine is carrying a light load and running at a certain speed. If the load is increased, the speed must drop a slight amount before the governor can operate to admit steam sufficient to carry the load, and the engine continues to run at a slightly lower speed on the heavy load than it did on the light load. There is therefore a certain engine speed for each load.

Now, suppose that two alternators are running in parallel and that each is supplying half the amount of power taken by the system. If the external load is increased, the amount of power supplied to each alternator must also increase, and, if the load on the machines is to be kept equal, each engine must increase its power output by an equal amount. We have just seen that to increase the power output the engine speed must drop slightly, and as the alternators must always run in synchronism, it follows that both engines must, for a given increase in load, drop their speeds an equal amount. In other words, to secure equal division of load the engines must perform in exactly the same way as regards change in speed. If the speed of one alternator drops, its engine takes more steam and the leading alternator supplies cross-current, both tending to restore synchronism. The question, then, of proper division of load is one that relates more to the engines than to the alternators, and in choosing engines for this kind of work every effort should be made to have them alike as regards their change in speed with change in load. The engines may run at exactly the same speed for a given load, but if their speeds do not drop by the same amount with increase in load, the output will not divide properly between the machines.

When machines are belt-driven, great care must be taken to see that the pulleys are exactly the correct dimensions to give the speeds required for operating in synchronism; because, if this is not the case, there will be considerable belt slippage, and there will also be considerable cross-current between the two machines.

80. Hunting of Alternators.—When alternators are coupled directly to slow-moving steam engines, difficulty is frequently encountered in connection with their parallel operation. This is specially the case when the alternators deliver a current of high frequency. The machines **surge,** or **hunt,** that is, the speed may fluctuate during each revolution, thus causing large periodic cross-currents to flow between the machines and seriously affecting the voltage of the system. This surging may become so bad as to cause the machines to fall out of synchronism and render parallel operation impossible. If rotary converters or synchronous motors are operated from the alternators, surgings are also set up in them and the voltage fluctuation and sparking caused thereby may be so serious as to make satisfactory operation very difficult to accomplish.

The cause of these surgings has been found in many cases to be due to periodic variations in the speed of the engine, and various methods have been tried to suppress them. The turning effort exerted on the crankpin of a steam engine is not uniform at all parts of the stroke, the pressure at the various points depending on the steam distribution in the cylinder or cylinders, on the position of the crankpin, angularity of the connecting-rod, etc. The result is, that while the speed of the engine may remain practically constant so far as the number of revolutions per minute is concerned, there will be momentary variations in speed during each revolution. It takes but a small momentary variation in angular velocity to throw the machines considerably out of phase, especially if the alternator has a large number of poles. For example, if a direct-connected alternator has 60 poles, the angular distance between centers of

poles will be 6°, and this corresponds to a phase difference of 180°. The periodic variation in the angular velocity of the revolving field or armature sets up corresponding variations in phase difference and results in periodic surges of current between the machines. This trouble has been investigated quite fully by Mr. W. L. R. Emmett*, who found that the energy necessary to maintain these current oscillations was in a number of cases supplied from the steam cylinders of the engines, and that it could be largely prevented by fixing the governor so that it would not respond to these sudden variations and admit the steam necessary to maintain them. The governor must, however, be capable of responding to changes in the regular load on the machine, otherwise enough power would not be furnished to the alternator to enable it to carry its share of the load. In order to fix the governor so that it would respond to gradual changes in the load, but not to momentary oscillations, it was provided with a dashpot similar to that shown in Fig. 27. This dashpot was designed by Messrs. H. W. Buck and Harte Cook. It consists of a cylinder *A* in which a piston *B* moves; two by-passes *b*, *b'* are provided, and at the end of each is placed a valve *c* or *c'* ordinarily held closed by springs *d*, *d'*. Each valve is provided with a small by-pass *e*, *e'*, and the whole cylinder, including the ports, is filled with

FIG. 27

*Transactions of American Institute of Electrical Engineers, October 25, 1901.

heavy oil. Unless valves c, c' are raised, the only passage for the oil, to allow movement of the piston, is through the small ports, and the piston is therefore practically locked. A sudden fluctuation in the governor will not move c or c', but a steady pressure on the piston, due to a prolonged raising or lowering of the speed, will move them, and the oscillations of the governor and steam in the cylinders are thereby damped out, thus suppressing the hunting action of the alternators.

81. In order to prevent hunting effects, engine builders have endeavored to secure uniform angular velocity of their engines. In some cases this is accomplished by the use of very heavy flywheels, but it is a question whether heavy flywheels are on the whole advisable. Some authorities claim that the momentum of heavy flywheels tends to maintain the oscillations, and that it is better to use fairly light flywheels and design the engine so that the turning effort on the shaft will be nearly uniform. By using two or more engines coupled to the same shaft with their cranks at the proper angle to each other, this result can be attained quite closely. This is readily accomplished by cross-compound engines, either horizontal or vertical, and both types are largely used for driving alternators. In the casé of the large alternators of the Manhattan Elevated Railway, New York, each alternator is driven by four engines, two of which are vertical and two horizontal. There is a crankpin at each end of the shaft, and to it is connected one vertical and one horizontal engine. The cranks are displaced 135° and since the four cylinders give eight impulses during each revolution, the turning moment is so uniform that no flywheel other than the revolving field of the alternator is necessary.

82. Use of Damping Devices.—Another method that has been used to prevent hunting is to provide special windings or conductors on the alternator field, so that the currents set up in them will oppose any shifting action and thus retard the oscillations. This device has been used much more on European alternators than on those built in America.

Fig. 28 (*a*) shows the method of arranging a damper (French amortisseur) of this kind, due to Hutin and Leblanc. *A* is the laminated pole piece of a revolving field alternator and is provided with the usual exciting coil *B*. Near the surface of the pole piece are a number of slots in which copper bars *c* are placed. These bars are connected together at each end of the pole by means of copper straps, thus forming the bars into a number of closed circuits similar to the squirrel-cage armature of an induction motor. As long as the magnetic flux passing from the pole face into the armature remains stationary with respect to the pole face, no currents are set up in the bars. If, however, there is any momentary shifting of the field, heavy currents are set up in the bars, and

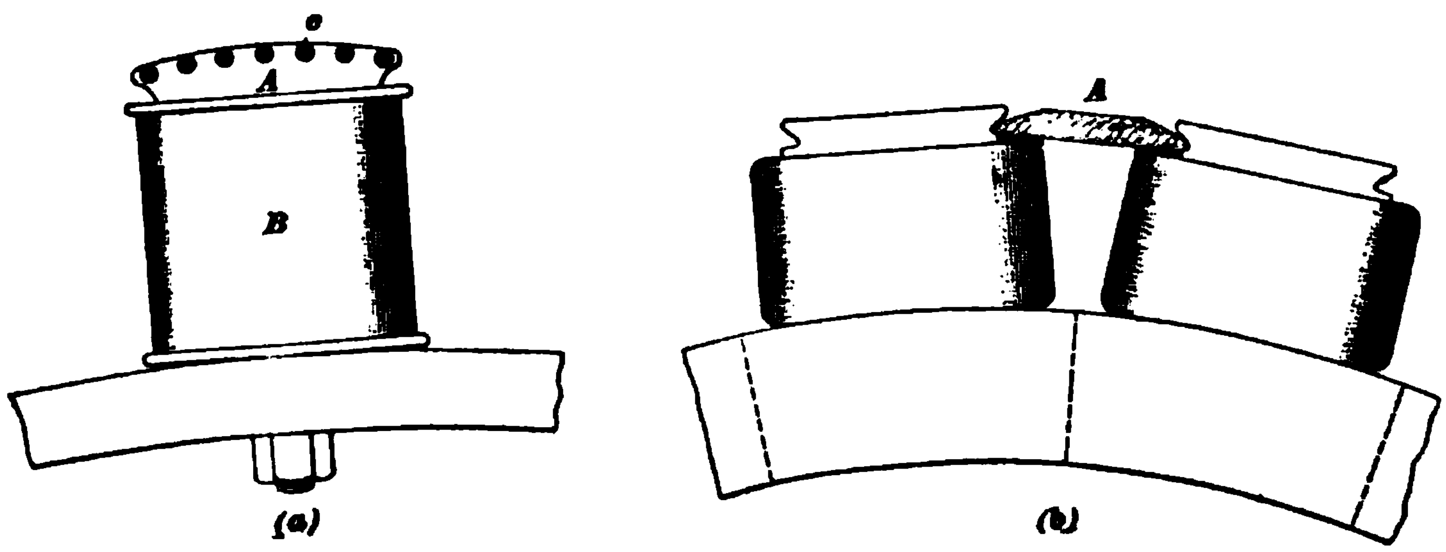


FIG. 28

these currents dampen the motion, thus smoothing out any tendency toward fluctuation. Fig. 28 (*b*) shows a field construction used by the Westinghouse Company that has somewhat the same effect. Copper bridges *A* are placed between the poles; these serve to hold the coils in place and dampen hunting effects.

83. Hunting sometimes occurs even when the alternators are driven by prime movers, such as steam or water turbines, that give an absolutely uniform angular velocity. In this case the effect is due to certain relations between the properties of the electric circuit, such as its self-induction, capacity, etc., and the momentum of the moving masses of the machinery. The result is a cumulative pendulum effect that may be overcome by changing some of the above properties

of the circuit or by damping the alternator, synchronous motors, rotary converters, or other devices on the system. For example, a change in field excitation will frequently overcome the difficulty. Fig. 29 shows another arrangement used for preventing hunting of rotary converters and alternators. The pole piece is provided with a slot *b* in the center, in which is placed a heavy copper bar. The pole is also encircled by a heavy conductor forming two local circuits, in which heavy currents are set up if there is any shifting of the field. Rotary converters are also frequently provided with copper bridges between the poles, about as shown in Fig. 28 (*b*), to dampen the hunting. Fig. 30 shows an anti-hunting device used on General Electric converters. The copper casting *a*, *b*, *e*, *f* bridges across the pole tips and is held in place by a bolt passing through *a b*. By drawing up this bolt, edges *e f* are forced apart against the pole tips. The sides *c d* lie in slots provided in the pole faces.

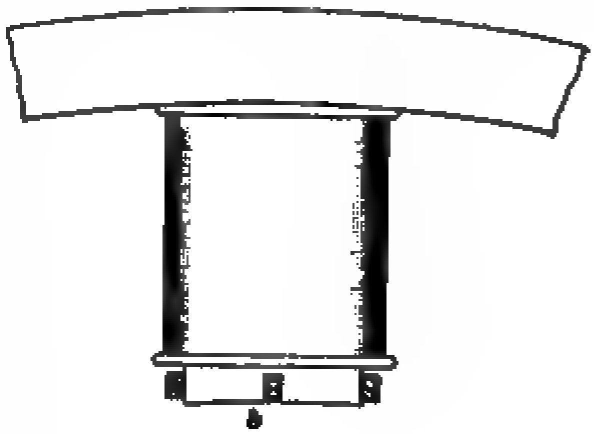


FIG. 29

84. Generally speaking, the practice in America is to obtain engines that will give a nearly uniform angular velocity, though damping devices are also used. Damping devices add to the cost and also slightly lower the efficiency of the machines to which they are applied. Engine builders will now guarantee engines not to give a departure from uniform motion during a revolution that will cause more than $2\frac{1}{2}°$ to $3°$ of phase displacement of the E. M. F. furnished by each of the alternators or a total maximum phase displacement of $5°$ to $6°$. If the displacement does not exceed this amount, the operation should be satisfactory. In America

damping devices are more commonly used on rotary converters than on alternators.

When steam-driven alternators are being synchronized, it is necessary to have some convenient means of controlling the engine speed from the switchboard. One way of doing this is to have a small reversible electric motor attached to the governor and arranged so that it can vary the tension on a spring attached to the governor weights or vary the position of a weight on a lever arm attached to the governor. This motor is readily started, stopped, or reversed from the switchboard, so that the attendant has the speed of the engine under control and can make the slight variations in speed necessary to secure equality of frequency. Also, this device allows the point of cut-off to be varied when the engine is in regular operation, thus regulating the amount of power supplied to the alternator. As explained above, the current delivered by each alternator when running in synchronism depends on the amount of power supplied to the alternator, so that by adjusting the governor, the output of each machine, as shown by its indicating wattmeter on the switchboard, can be regulated.

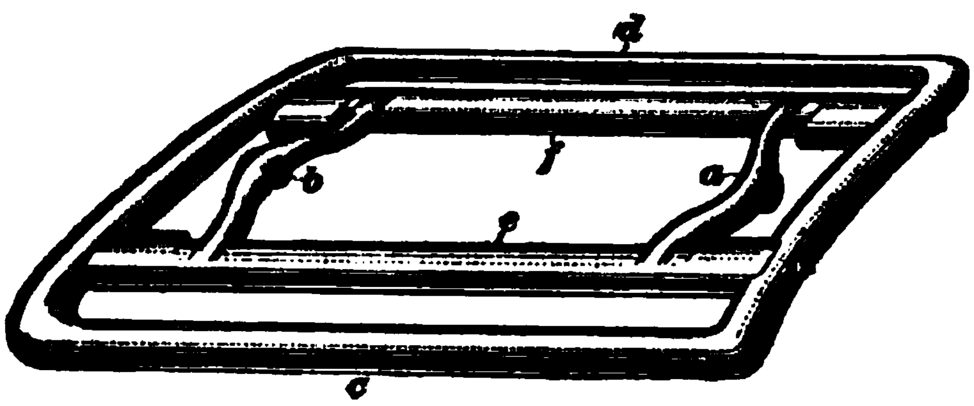


FIG. 30

85. Compound-Wound Alternators in Parallel. Most of the large alternators now installed are of the revolving field type and are not generally provided with a compound field winding. For large units it is found that a carefully designed machine gives sufficiently close voltage regulation with a plain, separately excited winding, so that the extra complication of compound field excitation is not warranted. Where a compound winding is used on the fields, it is necessary to provide an equalizing connection somewhat similar to that used for a direct-current machine. Fig. 31 shows the connections necessary for running two

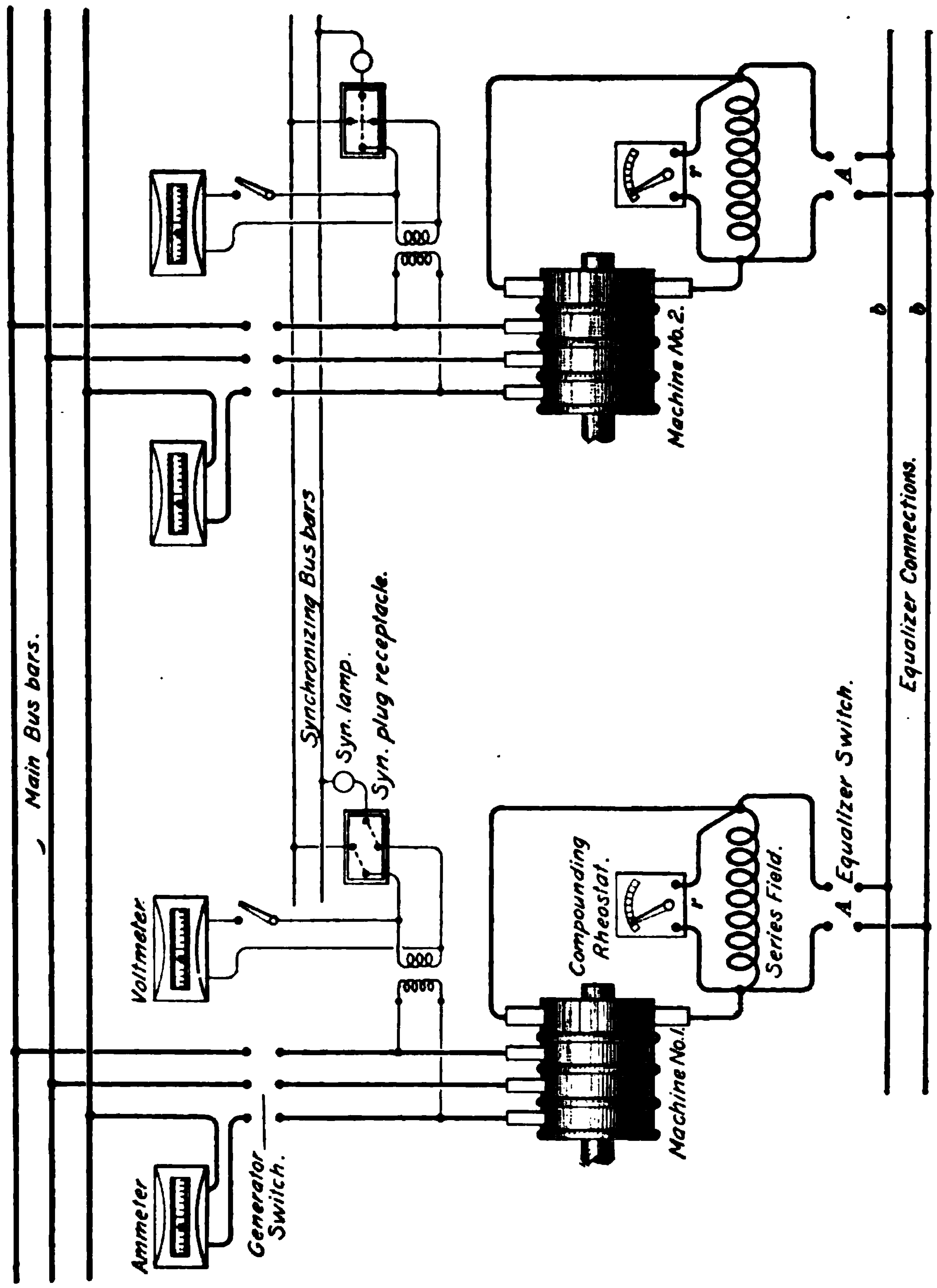

Main Bus bars.
Synchronizing Bus bars
Syn. lamp.
Syn. plug receptacle.
Voltmeter
Ammeter
Generator Switch.
Machine No.1.
Machine No.2.
Compounding Rheostat.
Series Field.
Equalizer Switch.
Equalizer Connections.
A
A
r
r
b
b

FIG. 31

compound-wound, three-phase alternators in parallel, the connections for the separately excited field being omitted in order to simplify the diagram. The terminals of the series-field winding on each machine connect through switches *A*, *A* to the equalizing wires *b*, *b*. An adjustable resistance *r'* is connected across each field, so that the effect of the series-coils can be varied to suit the character of the load on the machines. With the synchronizing connections shown in the figure, the lamps will be bright at synchronism, though the lamps could be made dark by simply changing the cross-connections used with the plug on the machine being synchronized. In this case an ammeter is used in one phase only, and is all that is necessary to indicate the current, provided the load is of such a nature that it is not liable to become unbalanced. In many cases it is customary to use an ammeter in each line, so that the current in all three phases will be indicated.

LINE CONSTRUCTION

INTRODUCTION

1. Line construction may be considered conveniently under two heads: (*a*) *overhead construction;* (*b*) *underground construction.*

For nearly all work in towns and small cities or for cross-country work, the lines are supported on poles. In cities, the current is now usually distributed, at least so far as the central part of the cities is concerned, by means of wires or cables run in underground tubes or ducts. This method is, of course, much more expensive than the overhead method; but the large increase in the number of wires used for different electrical purposes has rendered underground distribution in cities almost absolutely necessary.

LINE CONDUCTORS

2. The line wire is, in the vast majority of cases, of *copper*. *Aluminum* is now coming into use for this purpose, and in the future it may replace copper for some lines of work. *Iron* or *steel* is seldom used for a line conductor, because its resistance is too high. There is one case, however, in which it is largely used as a return conductor, and that is in connection with electric railways, where the current is led back to the power house through the rails.

COPPER CONDUCTORS

3. Bare and Insulated Wires.—Line conductors are usually in the form of **copper wire** of round cross-section whenever the conductor is of moderate size. For conductors

of large cross-section, stranded cables are used, made up of a number of strands of small wire twisted together. This construction makes the conductor flexible and easy to handle. When these wires or cables are strung in the air, they are usually insulated by a covering that consists of two or three

FIG. 1

braids of cotton, soaked in a weather-proof compound composed largely of pitch or asphalt. For underground work, the conductor is first insulated with rubber, or paper soaked in

FIG. 2

compound, and the whole covered with a lead sheath to keep out moisture. Fig. 1 shows a stranded cable for underground work provided with an insulating layer of paper and a lead

FIG. 3

sheath. Fig. 2 shows an ordinary triple-braid weather-proof overhead line wire, and Fig. 3 a weather-proof overhead cable. When the pressure used on the line is very high, say 10,000 volts or more, bare wires are generally used, because the ordinary weather-proof insulation is of little or no

protection against such pressures and only gives a false appearance of security. The practice for such lines is, therefore, to use bare wire and to insulate it thoroughly by means of specially designed insulators.

WIRE GAUGES

4. Various standards or **wire gauges** have been adopted by different manufacturers, but the safest and best way is to express the diameter of a wire in *mils*, or thousandths of an inch, and its area of cross-section in *circular mils*. The American, or Brown & Sharpe, gauge is used almost exclusively in America in connection with electrical work, but it is always well to give the diameter of the wire as well as its gauge number, so as to avoid any possibility of mistake. When wires or cables larger than the regular B. & S. sizes are specified, their cross-section is given in circular mils. Explanations regarding the B. & S. gauge and the expression of area in circular mils, etc. have already been given, so it will not be necessary to repeat them here. As we shall have occasion to refer to the B. & S. wire table frequently, Table I is repeated here for convenience. This gives the dimensions, weight, etc. of bare copper wire according to the B. & S. gauge for both annealed and hard-drawn wire; most wires and cables are of annealed copper. The use of hard-drawn copper is confined principally to trolley wire for street railways and telephone and telegraph line wires.

5. Table II gives the approximate weights of weather-proof line wire, such as is used for ordinary outside lines.

6. Table III gives the approximate dimensions of stranded insulated weather-proof cables for overhead work. Such cables are always designated by their area of cross-section in circular mils, and not by gauge number. In fact, any conductor larger than No. 0000 is usually designated by its area in circular mils. Cables such as those given in Table III are extensively used for street-railway feeders or for any other purpose requiring a large conductor.

TABLE I

DIMENSIONS, WEIGHT, ETC. OF BARE COPPER WIRE

American, or B. & S., Gauge

Gauge No., B. & S.	Diameter in Mils, or $\frac{1}{1000}$ Inch	Area in Circular Mils C. M. = d^2	Area in Square Inches Area = $\frac{d^2 \times .7854}{1,000,000}$	Weights—Specific Gravity, 8.89				Resistance at 68° F., in International Ohms, Based on Matthiessen's Standard				
				Pounds per 1,000 Feet	Pounds per Mile	Feet per Pound	Ohms per Pound, Annealed	Ohms per 1,000 Feet		Ohms per Mile		Feet per Ohm, Annealed
	d	d^2						Pure Annealed	Hard Drawn	Pure Annealed	Hard Drawn	
0000	460.00	211,600.	.16619	640.5	3,381.4	1.561	.00007639	.04893	.050036	.25835	.26419	20,440.
000	409.64	167,805.	.13179	508.0	2,682.2	1.969	.0001215	.06170	.063094	.32577	.33314	16,210.
00	364.80	133,079.	.10452	402.8	2,126.8	2.482	.0001931	.07780	.079558	.41079	.42007	12,850.
0	324.86	105.534.	.082887	319.5	1,686.9	3.130	.0003071	.09811	.10033	.51802	.52973	10,190.
1	289.30	83,694.2	.065732	253.3	1,337.2	3.947	.0004883	.1237	.12649	.65314	.66790	8,083.
2	257.63	66,373.0	.052128	200.9	1,060.6	4.977	.0007765	.1560	.15953	.82368	.84239	6,410.
3	229.42	52,634.0	.041339	159.3	841.09	6.276	.001235	.1967	.20114	1.0386	1.0621	5,084.
4	204.31	41,742.0	.032784	126.4	667.39	7.914	.001963	.2480	.25361	1.3094	1.3392	4,031.
5	181.94	33,102.0	.025999	100.2	529.06	9.980	.003122	.3128	.31987	1.6516	1.6889	3,197.
6	162.02	26,250.5	.020618	79.46	419.55	12.58	.004963	.3944	.40332	2.0825	2.1295	2,535.
7	144.28	20,816.0	.016351	63.02	332.75	15.87	.007892	.4973	.50854	2.6258	2.6850	2,011.
8	128.49	16,509.0	.012967	49.98	263.89	20.01	.01255	.6271	.64127	3.3111	3.3859	1,595.
9	114.43	13,094.0	.010283	39.63	209.24	25.23	.01995	.7908	.80876	4.1753	4.2769	1,265.
10	101.89	10,381.0	.0081548	31.43	165.95	31.82	.03173	.9972	1.0199	5.2657	5.3848	1,003.
11	90.742	8,234.0	.0064656	24.93	131.63	40.12	.05045	1.257	1.2854	6.6369	6.7869	795.3
12	80.808	6,529.9	.0051287	19.77	104.39	50.59	.08022	1.586	1.6218	8.3741	8.5633	630.7

13	71.961	5,178.4	.0040672	15.68	82.791	63.79	.1276	1.999	2.0443	10.555	10.794	500.1
14	64.084	4,106.8	.0032254	12.43	76.191	80.44	.2028	2.521	2.5779	13.311	13.612	396.6
15	57.068	3,256.7	.0025579	9.858	52.050	101.4	.3225	3.179	3.2508	16.785	17.165	314.5
16	50.820	2,582.9	.0020285	7.818	41.277	127.9	.5128	4.009	4.0996	21.168	21.646	249.4
17	45.257	2,048.2	.0016087	6.200	32.736	161.3	.8153	5.055	5.1692	26.691	27.294	197.8
18	40.303	1,624.3	.0012757	4.917	25.960	203.4	1.296	6.374	6.5183	33.655	34.416	156.9
19	35.890	1,288.1	.0010117	3.899	20.595	256.5	2.061	8.038	8.2196	42.441	43.400	124.4
20	31.961	1,021.5	.00080231	3.092	16.324	323.4	3.278	10.14	10.372	53.539	54.749	98.66
21	28.462	810.1	.00063626	2.452	12.946	407.8	5.212	12.78		67.479		78.24
22	25.347	642.4	.00050457	1.945	10.268	514.2	8.287	16.12		85.114		62.05
23	22.571	509.45	.00040015	1.542	8.142	648.4	13.18	20.32		107.29		49.21
24	20.100	404.01	.00031733	1.223	6.457	817.6	20.95	25.63		135.53		39.02
25	17.900	320.40	.00025166	.9699	5.121	1,031.	33.32	32.31		170.59		30.95
26	15.940	254.10	.00019958	.7692	4.061	1,300.	52.97	40.75		215.16		24.54
27	14.195	201.50	.00015827	.6100	3.221	1,639.	84.23	51.38		271.29		19.46
28	12.641	159.79	.00012551	.4837	2.554	2,067.	133.9	64.79		342.09		15.43
29	11.257	126.72	.000099536	.3836	2.025	2,607.	213.0	81.70		431.37		12.24
30	10.025	100.50	.000078936	.3042	1.606	3,287.	338.6	103.0		543.84		9.707
31	8.928	79.70	.000062599	.2413	1.274	4,145.	538.4	129.9		685.87		7.698
32	7.950	63.21	.000049643	.1913	1.010	5,227.	856.2	163.8		864.87		6.105
33	7.080	50.13	.000039368	.1517	.801	6,591.	1,361.	206.6		1,090.8		4.841
34	6.305	39.75	.000031221	.1203	.635	8,311.	2,165.	260.5		1,375.5		3.839
35	5.615	31.52	.000024759	.09543	.504	10,480.	3,441.	328.4		1,734.0		3.045
36	5.000	25.00	.000019635	.07568	.400	13,210.	5,473.	414.2		2,187.0		2.414
37	4.453	19.83	.000015574	.06001	.317	16,660.	8,702.	522.2		2,757.3		1.915
38	3.965	15.72	.000012345	.04759	.251	21,010.	13,870.	658.5		3,476.8		1.519
39	3.531	12.47	.0000097923	.03774	.199	26,500.	22,000.	830.4		4,384.5		1.204
40	3.145	9.89	.0000077634	.02993	.158	33,410.	34,980.	1,047.		5,528.2		.955

ALUMINUM CONDUCTORS

7. Mention has already been made of the fact that **aluminum** is being used for electrical conductors, because this metal can now be sold at a figure low enough to compete with copper. Its conductivity is only about 62 per cent. that of copper, so that for a conductor of the same resistance a larger cross-section is required. Aluminum is, however, so much lighter than copper that the larger cross-section can be used and still compete with the latter metal, although the cost per pound of the aluminum is considerably

TABLE II

APPROXIMATE WEIGHTS OF WEATHER-PROOF WIRE

(American Electrical Works)

TRIPLE-BRAIDED INSULATION

Size	Feet per Pound	Pounds per 1,000 Feet	Pounds per Mile	Carrying Capacity, Amperes, National Board Fire Underwriters
0000	1.34	742	3,920	312
000	1.64	609	3,215	262
00	2.05	487	2,570	220
0	2.59	386	2,040	185
1	3.25	308	1,625	156
2	4.10	244	1,289	131
3	5.15	194	1,025	110
4	6.26	160	845	92
5	7.46	134	710	77
6	9.00	111	585	65
8	13.00	73	385	46
10	20.00	50	265	32
12	29.00	35	182	23
14	38.00	26	137	16
16	48.00	21	113	8
18	67.00	15	81	5

TABLE II—(*Continued*)

DOUBLE-BRAIDED INSULATION

Size	Feet per Pound	Pounds per 1,000 Feet	Pounds per Mile	Carrying Capacity, Amperes, National Board Fire Underwriters
0000	1.40	711	3,754	312
000	1.75	570	3,010	262
00	2.29	436	2,300	220
0	2.81	355	1,875	185
1	3.56	281	1,482	156
2	4.49	223	1,175	131
3	5.45	184	969	110
4	6.82	147	774	92
5	9.10	110	580	77
6	10.35	97	510	65
8	15.52	64	340	46
10	22.00	45	237	32
12	40.00	25	132	23
14	56.00	18	95	16
16	76.00	13	69	8
18	100.00	10	53	5

higher. Line-construction work is somewhat easier with aluminum cable than with copper cable of the same conductivity, since the aluminum cable is the lighter one. A complete system of mechanical joints has been devised for connecting together lengths of aluminum cables. These devices enable the linemen to make efficient joints rapidly.

In Table IV are given the properties of stranded aluminum wire, and in Table V, the resistance data of pure aluminum wire. A comparison of some of the properties of aluminum and copper is given in Table VI.

TABLE III

STRANDED WEATHER-PROOF FEED-WIRE

(*Roebling's*)

Circular Mils	Outside Diameters Inches	Weights Pounds		Approximate Length on Reels Feet	Carrying Capacity, National Board Fire Underwriters
		1,000 Feet	Mile		
1,000,000	$1\frac{1}{2}$	3,550	18,744	800	1,000
900,000	$1\frac{13}{32}$	3,215	16,975	800	920
800,000	$1\frac{11}{32}$	2,880	15,206	850	840
750,000	$1\frac{5}{16}$	2,713	14,325	850	
700,000	$1\frac{9}{32}$	2,545	13,438	900	760
650,000	$1\frac{1}{4}$	2,378	12,556	900	
600,000	$1\frac{7}{32}$	2,210	11,668	1,000	680
550,000	$1\frac{3}{16}$	2,043	10,787	1,200	
500,000	$1\frac{1}{8}$	1,875	9,900	1,320	590
450,000	$1\frac{3}{32}$	1,703	8,992	1,400	
400,000	$1\frac{1}{16}$	1,530	8,078	1,450	500
350,000	1	1,358	7,170	1,500	
300,000	$\frac{15}{16}$	1,185	6,257	1,600	400
250,000	$\frac{29}{32}$	1,012	5,343	1,600	

TABLE IV

DIAMETERS AND PROPERTIES OF STRANDED ALUMINUM WIRE

(Conductivity at 62 in the Matthiessen Standard Scale)

Number B. & S. Gauge	Circular Mils	Diameters		Weight, in Pounds			Resistance in Ohms at 70° F. per 1,000 Feet
				Bare		Triple Braid Insulated	
		Decimal Parts of an Inch	Nearest 32d of an Inch	Per 1,000 Feet	Per Mile	Per 1,000 Feet	
	1,000,000	1.152	$1\frac{5}{32}$	920.	4,858	1,406.	.016726
	950,000	1.125	$1\frac{1}{8}$	874.	4,617	1,337.	.017606
	900,000	1.092	$1\frac{3}{32}$	828.	4,374	1,268.	.018585
	850,000	1.062	$1\frac{1}{16}$	782.	4,131	1,199.	.019679
	800,000	1.035	$1\frac{1}{32}$	736.	3,888	1,129.	.020907
	750,000	.996	1	690.	3,645	1,060.	.022301
	700,000	.963	$\frac{31}{32}$	644.	3,402	990.	.023894
	650,000	.928	$\frac{15}{16}$	598.	3,159	921.	.025734
	600,000	.891	$\frac{29}{32}$	552.	2,916	852.	.027878
	550,000	.854	$\frac{27}{32}$	506.	2,673	782.	.030411
	500,000	.814	$\frac{13}{16}$	460.	2,430	713.	.033450
	450,000	.772	$\frac{25}{32}$	414.	2,187	644.	.037170
	400,000	.725	$\frac{23}{32}$	368.	1,944	575.	.041818
	350,000	.679	$\frac{11}{16}$	322.	1,701	506.	.047789
	300,000	.621	$\frac{5}{8}$	276.	1,458	436.	.055755
	250,000	.567	$\frac{9}{16}$	230.	1,215	366.	.066905
0000	211,600	.522	$\frac{17}{32}$	195.	1,028	313.	.07904
000	167,805	.464	$\frac{15}{32}$	155.	816	253.	.09966
00	133,079	.414	$\frac{13}{32}$	123.	647	204.	.12569
0	105,534	.368	$\frac{3}{8}$	97.	513	165.	.15849
1	83,694	.328	$\frac{11}{32}$	77.	407	135.	.19982
2	66,373	.291	$\frac{9}{32}$	61.	323	112.	.25200
3	52,634	.261	$\frac{1}{4}$	48.5	256	93.5	.31778
4	41,742	.231	$\frac{7}{32}$	38.5	203	76.5	.40067
5	33,102	.206	$\frac{7}{32}$	30.2	161	56.0	.50526
6	26,250	.180	$\frac{3}{16}$	24.1	128	47.0	.63720

TABLE V

RESISTANCES OF PURE ALUMINUM WIRE*

Am. Gauge, B. & S. No.	Resistances at 70° F. Ohms per 1,000 Feet	Ohms per Mile	Feet per Ohm	Ohms per Pound
0000	.07904	.41730	12,652.	.00040985
000	.09966	.52623	10,034.	.00065102
00	.12569	.66362	7,956.	.0010364
0	.15849	.83684	6,310.	.0016479
1	.19982	1.0552	5,005.	.0026194
2	.25200	1.3305	3,968.	.0041656
3	.31778	1.6779	3,147.	.0066250
4	.40067	2.1156	2,496.	.010531
5	.50526	2.6679	1 975.	.016749
6	.63720	3.3687	1,569.	.026628
7	.80350	4.2425	1,245.	.042335
8	1.0131	5.3498	987.0	.067318
9	1.2773	6.7442	783.0	.10710
10	1.6111	8.5065	620.8	.17028
11	2.0312	10.723	492.4	.27061
12	2.5615	13.525	390.5	.43040
13	3.2300	17.055	309.6	.68437
14	4.0724	21.502	245.6	1.0877
15	5.1354	27.114	194.8	1.7308
16	6.4755	34.190	154.4	2.7505
17	8.1670	43.124	122.5	4.3746
18	10.300	54.388	97.10	6.9590
19	12.985	68.564	77.05	11.070
20	16.381	86.500	61.06	17.595
21	20.649	109.02	48.43	27.971
22	26.025	137.42	38.44	44.450
23	32.830	173.35	30.45	70.700
24	41.400	218.60	24.16	112.43
25	52.200	275.61	19.16	178.78
26	65.856	347.70	15.19	284.36
27	83.010	438.32	12.05	452.62
28	104.67	552.64	9.55	718.95
29	132.00	697.01	7.58	1,142.9
30	166.43	878.80	6.01	1,817.2
31	209.85	1,108.0	4.77	2,888.0
32	264.68	1,397.6	3.78	4,595.5
33	333.68	1,760.2	3.00	7,302.0
34	420.87	2,222.2	2.38	11,627.
35	530.60	2,801.8	1.88	18,440.
36	669.00	3,532.5	1.50	29,352.
37	843.46	4,453.0	1.19	46,600.
38	1,064.0	5,618.0	.95	74,240.
39	1,341.2	7,082.0	.75	118,070.
40	1,691.1	8,930.0	.59	187,700.

*Conductivity at 62 in the Matthiessen standard scale. Pure aluminum weighs 167.111 pounds per cubic foot.

Calculated on the basis of Dr. Matthiessen's standard, namely, the resistance of a pure soft copper wire 1 meter long, having a weight of 1 gram = .141729 international ohm at 0° C.

TABLE VI

COMPARISON OF PROPERTIES OF COPPER AND ALUMINUM

Properties	Aluminum	Copper
Conductivity (for equal sizes)	.61 to .63	1
Weight (for equal sizes)	.33	1
Weight (for equal length and resistance)	.47	1
Ratio of prices per pound in order that the total cost of either material will be the same (for equal length and resistance)	2.13	1
Ordinary price ratios (for equal length and resistance)	.85 to .9	1
Temperature coefficient, per degree F.	.002138	.002155
Resistance of mil-foot (20° C.)	18.73	10.05
Specific gravity	2.5 to 2.68	8.89 to 8.93
Breaking strength (wires of equivalent conductivity)	1	1
Tensile strength (pounds per square inch, hard drawn)	20,000 to 35,000	20,000 to 60,000
Coefficient of expansion, per degree F.	.0000128	.0000093

IRON WIRE

8. Iron wire is used extensively for telegraph and telephone work. The approximate value of the resistance per mile of a good iron wire may be determined by the formula

$$R = \frac{360,000}{d^2} \qquad (1)$$

where d = diameter of wire in mils.

9. For **steel wire,** which is often used in place of iron wire, this formula becomes approximately

$$R = \frac{470,000}{d^2} \qquad (2)$$

The various grades of iron wire on the market are termed "Extra Best Best," "Best Best," and "Best"; the resistance of the different grades are shown in Table VII.

TABLE VII

DIMENSIONS AND RESISTANCE OF IRON WIRE

Number B. W. G.	Diameter in Mils = d	Area in Circular Mils = d^2	Weight Pounds		Breaking Strength Pounds		Resistance per Mile at 68° F.		
			1,000 Feet	1 Mile	Iron	Steel	E. B. B.	B. B.	Steel
0	340	115,600	304.0	1,607	4,821	9,079	2.93	3.42	4.05
1	300	90,000	237.0	1,251	3,753	7,068	3.76	4.40	5.20
2	284	80,656	212.0	1,121	3,363	6,335	4.19	4.91	5.80
3	259	67,081	177.0	932	2,796	5,268	5.04	5.90	6.97
4	238	56,644	149.0	787	2,361	4,449	5.97	6.99	8.26
5	220	48,400	127.0	673	2,019	3,801	4.99	8.18	9.66
6	203	41,209	109.0	573	1,719	3,237	8.21	9.60	11.35
7	180	32,400	85.0	450	1,350	2,545	10.44	12.21	14.43
8	165	27,225	72.0	378	1,134	2,138	12.42	14.53	17.18
9	148	21,904	58.0	305	915	1,720	15.44	18.06	21.35
10	134	17,956	47.0	250	750	1,410	18.83	22.04	26.04
11	120	14,400	38.0	200	600	1,131	23.48	27.48	32.47
12	109	11,881	31.0	165	495	933	28.46	33.30	39.36
13	95	9,025	24.0	125	375	709	37.47	43.85	51.82
14	83	6,889	18.0	96	288	541	49.08	57.44	67.88
15	72	5,184	13.7	72	216	407	65.23	76.33	90.21
16	65	4,225	11.1	59	177	332	80.03	93.66	110.70
17	58	3,364	8.9	47	141	264	100.50	120.40	139.00
18	49	2,401	6.3	33	99	189	140.80	164.80	194.80

GERMAN-SILVER WIRE

10. German-silver wire is used principally in resistance boxes or electrical instruments where a high resistance is required. The resistance of this wire varies greatly according to the materials and methods of manufacture used. It is an alloy of copper, nickel, and zinc, and has a resistance anywhere from 18 to 28 times that of copper. Its resistance changes only to a small extent with changes in temperature, a feature of value in connection with rheostats and resistance boxes.

Table VIII gives some of the properties of German-silver wire containing 18 or 30 per cent. of nickel.

TABLE VIII

GERMAN-SILVER WIRE

(Roebling's)

Number B. & S. Gauge	Resistance per 1,000 Feet International Ohms		Maximum Current Carrying Capacity in Amperes
	18-Per-Cent. Wire	30-Per-Cent. Wire	18-Per-Cent. Wire
6	7.20	11.21	
7	9.12	14.18	
8	11.54	17.95	
9	14.55	22.63	
10	18.18	28.28	8.5
11	22.84	35.53	5.4
12	28.81	44.82	4.6
13	36.48	56.75	3.8
14	46.17	71.82	3.2
15	58.21	90.55	2.7
16	72.72	113.12	2.3
17	93.40	145.29	1.9
18	118.20	183.87	1.65
19	145.94	227.02	1.21
20	184.68	287.28	.99
21	232.92	362.32	.88
22	295.38	459.48	.66
23	370.26	575.96	.55
24	468.18	728.28	.488
25	590.22	918.12	.434
26	748.08	1,163.68	.385
27	937.98	1,459.08	.343
28	1,191.24	1,853.04	
29	1,481.22	2,304.12	
30	1,891.8	2,942.8	
31	2,388.6	3,715.6	
32	2,955.6	4,597.6	
33	3,751.2	5,835.2	
34	4,764.6	7,411.6	
35	6,031.8	9,382.8	
36	7,565.4	11,768.4	

OVERHEAD CONSTRUCTION

POLES

11. Selection of Poles.—The poles used to the greatest extent in this country are of the following kinds of wood: Norway pine, chestnut, cypress, and white cedar. The average lives of these, under average conditions, are placed by good authority at the following values: Norway pine, 6 years; chestnut, 15 years; cypress, 12 years, white cedar, 10 years. Cedar poles are undoubtedly used to the greatest extent. Considering their strength, they are light in weight, and, by some authorities, are considered the most dùrable, when set in the ground, of any American wood suitable for pole purposes. In some of the Western States, California redwood is used for poles.

12. Sizes of Poles.—The best lines in this country use no poles having tops less than 22 inches in circumference. If the poles taper at the usual rate, the specification that a pole shall have a top 22 inches in circumference, or approximately 7 inches in diameter, is usually sufficient, for the diameter at the butt will then be approximately correct, no matter what may be the length of the pole. When a pole line has to carry but a few small wires, it is not necessary to have them as large as 7 inches at the top, and poles with a 5-inch top will answer every purpose. For long-distance transmission work, only the most substantial line construction is allowable, because every precaution must be taken to make the service continuous. Long transmission lines usually have to carry heavy wires, and moreover they are often in very exposed localities; for this class of work, therefore, specially heavy poles are used. The length of poles used in any given case is fixed by several considerations. It will

depend to some extent on the number of cross-arms to be accommodated, but more frequently the length is determined by the location of the pole. In any given transmission line it is necessary to use a number of different pole lengths and select the poles so that the tops will be graded, thus avoiding ups and downs in the wire as much as possible. A poorly graded line requires a greater length of wire than a well graded one, and this is objectionable not only on account of the extra cost of the wire, but also because of the larger line loss due to the larger resistance. Table IX shows the size of poles used on the Bay Counties high-tension transmission

TABLE IX

DIMENSIONS OF POLES

Height Feet	Diameter of Top Inches	Diameter of Butt Inches	Depth in Ground Feet
25	8	12	5
40	9	14	6
45	10	15	6½
50	11	16	7½
60	12	18	8

line in California*. Where angles occur in the line, the poles are set 1 foot deeper than shown by the figures in the last column of the table.

13. Spacing of Poles.—Practice varies as to the spacing of poles. Of course, the number and sizes of the wires to be carried are the most important considerations in determining this point, but the climatic conditions, especially with regard to heavy wind and sleet storms, should also be considered. In general, it may be said that the best lines carrying a moderate number of wires use 40 poles to the mile, while for exceptionally heavy lines, the use of 52 poles to the mile, or 1 pole every 100 feet, is not uncommon practice.

*Journal of Electricity, Power, and Gas, Vol. XI, No. 8.

As a general rule, which it is safe to follow in the majority of cases, 35 or 40 poles to the mile should be used. For city work, the poles should be set on an average not farther apart than 125 feet.

CROSS-ARMS

14. The **cross-arms** should be made of well-seasoned, straight-grained Norway pine, yellow pine, or creosoted white pine. Cross-arms are made in standard sizes, the

FIG. 4

length of the arm depending on the number of pins it is intended to hold. The standard cross-arm is $3\frac{1}{4}$ inches by $4\frac{1}{4}$ inches, and varies in length usually from 3 to 8 feet. They are usually bored for $1\frac{1}{2}$-inch pins and provided with holes for two $\frac{5}{8}$-inch bolts. The arms are generally braced by flat iron braces, about $1\frac{1}{4}$ inches wide by $\frac{1}{4}$ to $\frac{3}{8}$ inch thick. These braces are shown in Fig. 4, which gives a view of an ordinary pole top provided with two 4-pin cross-arms. This pole top represents the style of construction suitable for fairly light work, such as is used for local light and

power distribution. For long transmission lines, heavier cross-arms are used. For example, those used by the Standard Company, of California, on a line designed to handle current at 60,000 volts, are $5\frac{3}{4}$ inches by $5\frac{3}{4}$ inches, and the holes for the pins are 42 inches apart, this wide distance between the wires being necessary on account of the high voltage. The older Niagara line used cross-arms 4 inches by 6 inches, and the later line 5 inches by 6 inches.

15. Fig. 5 shows the pole top used on the first Niagara transmission line. It was designed to accommodate twelve

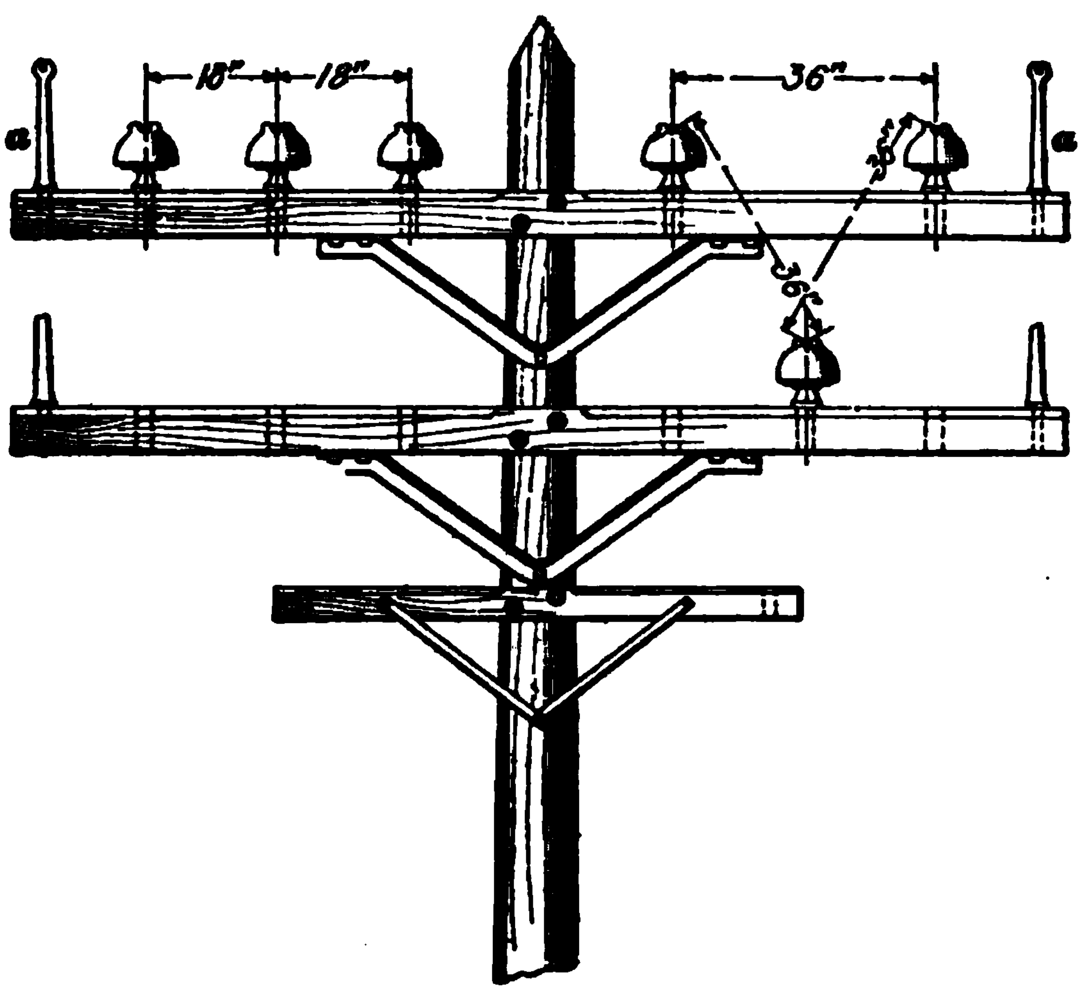


FIG. 5

transmission wires, the insulators being placed side by side on the cross-arms as shown in the left-hand half of the figure. It was found that this arrangement did not work well because it was an easy matter to start short circuits between the wires, and the arc thus started traveled along the line wires until the power was shut off. By adopting the triangular arrangement shown at the right, the distance between the wires was doubled and all three wires made equidistant from each other. The apex of the triangle formed by the wires was placed downwards, as this arrangement

makes it more difficult to lodge sticks or wires across the circuit than if the single wire is placed on the top arm with the other two beneath it, though the latter arrangement is used quite often. The Niagara line is designed to operate at 20,000 volts. The supports *a*, *a* at each end of the cross-arms were intended to hold barb wire that was grounded at regular intervals in order to conduct off lightning discharges. The barb wire was also intended to act to a certain extent as a guard wire to prevent articles from falling on the line. It was found, however, that sleet and snow caused these guard wires to break and fall across the lines

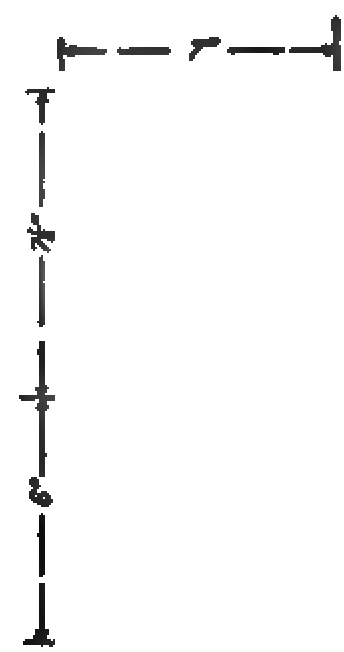
FIG. 6

FIG. 7

thus giving rise to so much trouble that they were finally removed. Barb wire is nevertheless used successfully in connection with a number of transmission plants, and affords an efficient protection against lightning, but it is necessary to use wire that is heavy enough to stand the strains put on it. Ordinary light barb wire as used for fences is not heavy enough for work where it has only one support in, say, every 100 feet, as is the case on a pole line. Another method that is sometimes used for arranging two three-phase circuits is to use three cross-arms with two wires on each cross-arm, the pins being so placed that the wires come at the corners of a regular hexagon.

PINS

16. One style of pin by which insulators are mounted on cross-arms is shown in Fig. 6. This shows the ordinary pin used for light lines; pins used for heavy long-distance lines are considerably larger and stronger. They may be made of locust, chestnut, or oak (the woods being preferred in the order named), and are turned with a coarse thread on the end on which the insulator is to be secured; the shank *K* is 1½ inches in diameter.



(a) (b)

Fig. 8 Fig. 9

The pin should be secured in the hole by driving a nail through the arm and the shank. This renders it difficult to extract the shank of the pin in case a new one is required; but, on the other hand, it prevents the pin pulling out, which sometimes occurs when this precaution is not taken. For heavy lines, pins having an iron bolt passing through them are sometimes used. Fig. 7 shows a pin of this kind, designed by F. Locke, with a heavy insulator for carrying a cable in the groove *a*.

In the case of high-tension, long-distance lines, exceptionally strong pins should be used. These are made of wood, because with high pressures any metal is objectionable near the insulator. Fig. 8 shows the style of pin used by the Standard Company previously referred to. These pins are made of blue gum wood (*Eucalyptus*), specially treated with linseed oil to prevent them from absorbing moisture. This pin is also shown in Fig. 14 in connection with the insulator that it supports. Fig. 9 (*a*) and (*b*) shows two styles of pin used on the Niagara transmission lines; (*b*) is the old-style pin, which was found to be too weak; (*a*) shows the heavier pin used on the later line. Note that in (*a*) the hole for the pin does not pass completely through the cross-arm. About 1 inch of wood is left at the bottom, as this is found to greatly strengthen the cross-arm.

FIG. 10

FIG. 11

17. Insulators in this country are usually made of glass, while in Europe porcelain is more commonly used. Porcelain, when new, is a better insulator than glass; but it is more costly, and under the action of cold the glazed surface becomes cracked. When this happens, the moisture soaks into the interior structure, and its insulating quality is greatly impaired. Tests recently made have shown that when newly put up, the insulation resistance of porcelain insulators is from 4 to 8 times better than glass, but that, along railroads and in cities, smoke forms a thin film on each material, so that at the end of a few months their insulating properties are nearly alike. On country roads, away from railroad

tracks, the porcelain insulators maintain a higher insulation than the glass during rain storms, but in fine weather it is not so high. Porcelain has an advantage over glass in that it is not so brittle, and therefore is less likely to break when subjected to mechanical shocks. It does not condense and retain on its surface a thin film of moisture so readily as glass, i. e., it is less hygroscopic. On the other hand, glass insulators are not subject to such an extent as porcelain to the formation of cocoons and cobwebs under them, the transparency of the glass serving to allow sufficient light to pass through the insulator to render it an undesirable abode for spiders and worms. As cocoons, cobwebs, etc. serve to lower the insulation of the line to a great extent, this is an advantage that, in this country, it is not well to overlook.

FIG. 12

FIG. 13

18. Types of Insulators.—For ordinary work with moderate pressures, glass insulators are used. The style of insulator will depend to some extent on the size of wire to be supported. Wires smaller than No. 6 or 8 B. & S. are seldom used for power transmission lines; hence, the glass insulators, as a rule, must be heavier than the kind used for telegraph or telephone work. Fig. 10 shows an insulator, known as the D. G. (deep groove), that is well adapted for ordinary lines. This insulator is so called to distinguish it from those with smaller grooves, such as are used for telephone or telegraph work. It is provided with two petticoats, or flanges, *a*, *b* over which leakage must take place before the current can leak from the wire to the pin. The use of a number of petticoats increases the leakage distance and provides a high insulation; insulators used on high-tension lines are provided with several

petticoats. When heavy cables are used, it is customary to carry them on especially heavy insulators and to tie down the cable on top of the insulator instead of tying it to the side. Fig. 7 shows a common type of such insulator; the cable rests in the groove *a* and is held in place by a tie-wire twisted around the cable and passing under the ears at *b*, *c*. Good quality glass insulators, such as those just described, may be used for any lines where the potential is not over 2,000 or 3,000 volts; for higher pressures, it is necessary to use a larger insulator giving a higher degree of insulation. Fig. 11 shows a Locke insulator of glass that is suitable for any pressure up to 5,000 volts. This insulator is 4½ inches in diameter, and, it will be noted, is provided with three petticoats, thus giving a long leakage distance from the wire to the pin. Fig. 12 shows a still larger insulator; this one is suitable for pressures up to 25,000 volts and is 5½ inches in diameter.

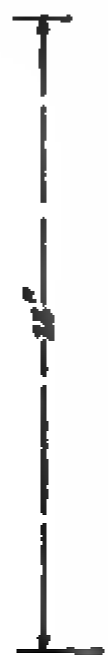


FIG. 11

For high pressures, porcelain insulators have been largely used; as yet there does not seem to be any settled opinion as to just which is the better, glass or porcelain, for this kind of work, and on some lines using very high pressures the insulators are made partly of porcelain and partly of glass. Fig. 13 shows a type of porcelain insulator used for one of the Niagara-Buffalo transmission lines. These insulators are elliptical, or helmet, shaped and have an eave, or ridge, *a* on each side, the object of which is to run off the water to the end of the

insulator, where it will drop clear of the cross-arm. Fig. 9 (*a*) shows a section of the later type of insulator used on the Niagara lines, and Fig. 14 shows a style that is used on high-tension lines in California that operate at pressures as high as 40,000 to 60,000 volts; in fact, lines equipped with these insulators have been operated experimentally at 80,000 volts. This insulator is made in two parts, the upper part being of porcelain and the lower of glass. The parts are cemented together by a mixture of sulphur and sharp sand, and the upper part is made of porcelain because moisture does not cling to it as readily as to glass. Glass offers a greater resistance to puncture than porcelain, so that by combining the two materials a very efficient insulator is obtained, and the cost is also reduced materially. The lower part of the pin is covered by a porcelain sleeve that protects the pin from any arc that might tend to strike from the eave of the insulator, and it also protects the pin from the weather. The upper part of the insulator is provided with a ridge around the edge and a projecting lip at one side, so that rain falling on the insulator drips clear of the cross-arm. These insulators are subjected to a test pressure of 120,000 volts for a period of 5 minutes in order to detect any defective insulators before they are put up on the line.

Fig. 15

TYING, SPLICING, ETC.

19. Tying.—Fig. 15 shows the method of tying that is commonly used for small insulators. The tie-wire *a* is from 12 to 16 inches in length and should be insulated to the same extent as the wire to be tied. The line wire is laid in

the groove of the insulator, after which the two ends of the tie-wire, which have been passed half way around the insulator, are wrapped tightly around the wire. Some linemen prefer to wrap one end of the tie-wire over and the other end under the line wire. Fig. 16 shows a method of tying used where the wire lies on top of the insulator as with the Niagara type. Fig. 17 shows the method of tying to the insulator shown in Fig. 14. In this case a No. 4 aluminum tie-wire is used to tie the aluminum cable.

FIG. 16

20. Splicing.—The American wire joint shown in Fig. 18 is generally used for splicing solid wires. The wires are placed side by side and each end wound around the other. All joints should be soldered. The rules of the National Board of Fire Underwriters require that all line joints shall be mechanically and electrically perfect before being soldered; i. e., solder should not be depended on to make the joints strong mechanically or efficient as an electrical conductor. In other words, soldering should always be done simply as a safeguard against any diminution in the electrical conductivity of the joint. Large copper cables are joined either by weaving the strands together and soldering, or by using a copper sleeve into which the ends of the cable are fastened.

FIG. 17

Aluminum wires and cables are very often joined by means of a mechanical coupling, as aluminum is not easily

soldered. Joints between aluminum wires of an area equal to No. 0000 B. and S. gauge, or less, are best made by means of a piece of flattened aluminum tubing, Fig. 19 (*a*), into which the two ends to be joined are inserted side by side. The tubing with the wires is then given from two and one-half

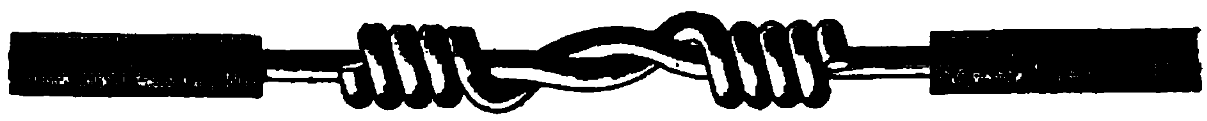
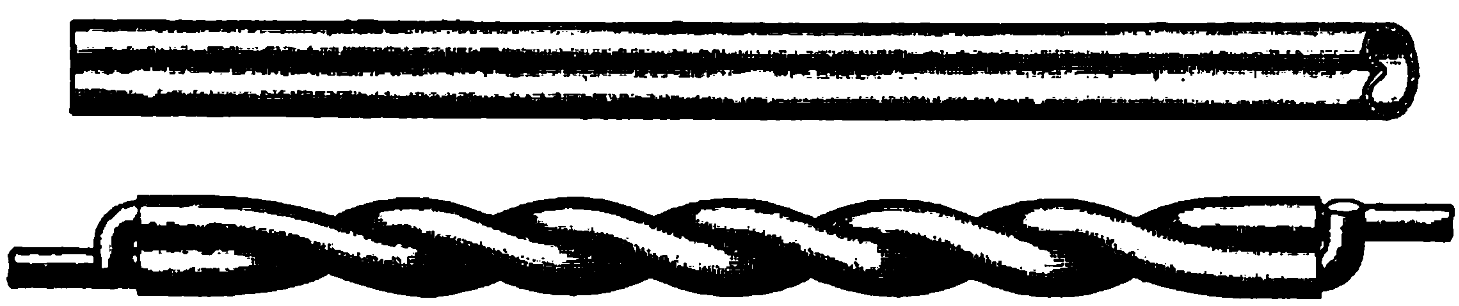


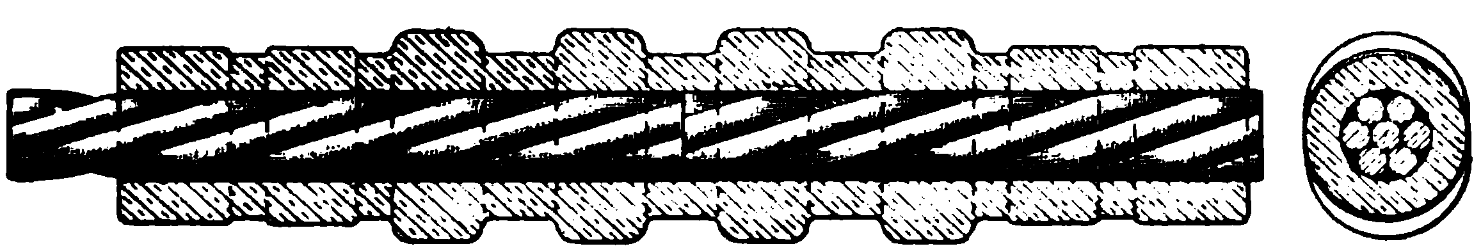
FIG. 18

to four complete twists. In some cases, cables having a cross-sectional area of 600,000 circular mils have been connected together by joints of this kind.

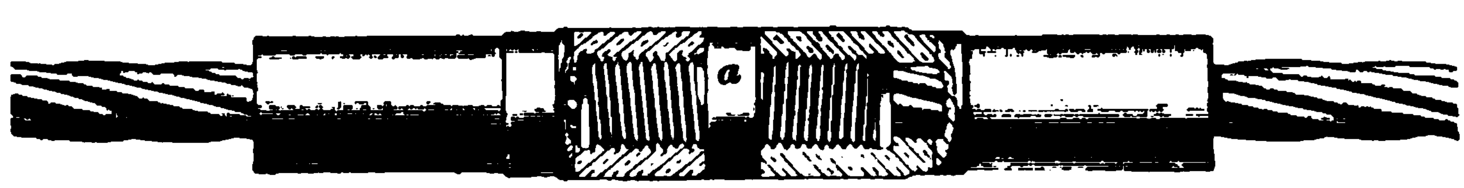
On account of the stiffness of large cables, joints of the compression type, one form of which is shown in Fig. 19 (*b*),



(a)



(b)



(c)

FIG. 19

are often used. The ends of the cable are inserted into a cast aluminum sleeve of proper size, the ends butting together in the center of the sleeve. The sleeve with its cables is then inserted between dies in a portable hydraulic jack, and sufficient pressure is applied to the dies to cause the metal of the sleeve and the metal of the cables to flow

together into a solid, homogeneous mass. When tested, the cable will be pulled in two instead of the ends of the cables pulling out of the sleeve.

A modified form of the joint just described is shown in Fig. 19 (*c*). Terminal pieces of aluminum are compressed on the ends of the cables at the factory. One terminal has a right-hand thread and the other terminal a left-hand thread. The ends of two cables are joined by screwing into the two terminals a right-and-left-hand threaded stud *a*, which draws the terminals into firm contact with the stud.

21. Stringing Aluminum Wire.—Owing to the physical properties of aluminum, care should be taken in stringing it not to pull it up with the same tension as copper wire. Aluminum wire should be pulled up so as to have about the same sag as would be allowed for copper wire with the same span.

Aluminum wire should not be pulled as hard as copper wire because of the difference in weight. One-third of the pull that would be used on a copper wire is sufficient to draw an aluminum wire up to the same deflection that the copper wire should have.

If the aluminum wire were pulled with the same amount of tension that would be used with a copper wire, the aluminum wire would be drawn up to a much smaller deflection than the copper wire would receive, and it would become too tight at low temperatures, possibly resulting in broken insulator pins and even cross-arms.

Table X shows the proper deflection of the aluminum wire at the center of the span, for various lengths of spans, and for various rises in temperature above the minimum temperature to which the wire will probably be subjected.

EXAMPLE.—Suppose an aluminum wire is strung on poles 200 feet apart. What deflection should be allowed at the center of the span, if the minimum temperature is assumed to be 10° F. below zero and the temperature at the time the wire is strung is 70° F.?

SOLUTION.—The difference in temperature between 10° F. below zero and 70° F. is 80°. In Table X, in the column for 200-ft. span

TABLE X

DEFLECTIONS OF ALUMINUM WIRE

(*Maximum Tension 11,000 Pounds per Square Inch*)

Rise Above Minimum Temperature Degrees F.	Length of Span, in Feet					
	200	180	160	140	120	100
	Deflection, in Inches					
0	6.30	5.30	4.20	3.1	2.20	1.70
10	7.00	5.70	4.50	3.4	2.40	1.75
20	7.80	6.40	5.10	3.8	2.80	1.90
30	8.80	7.25	5.75	4.5	3.20	2.20
40	10.20	8.40	6.70	5.2	3.80	2.70
50	12.00	9.80	7.80	6.4	4.60	3.30
60	14.00	11.50	9.40	7.5	5.60	4.00
70	16.50	14.00	11.50	9.2	7.00	5.20
80	19.75	17.00	14.25	11.4	8.90	6.80
90	23.10	20.00	16.80	13.8	10.30	8.75
100	26.60	23.30	20.00	16.6	13.10	10.80
110	29.75	26.60	23.00	19.5	16.25	13.10
120	33.45	29.75	25.75	22.2	18.70	15.20
130	36.75	32.80	28.70	24.5	20.80	17.20
140	40.00	35.75	31.50	26.8	22.80	18.80
150	43.00	38.40	33.60	29.1	24.80	20.30

and opposite the value of 80° F. rise in temperature, read the deflection value 19.75 in. Ans.

22. When stringing either copper or aluminum wire, it is customary to pull up a number of spans at a time. An experienced foreman of construction can usually estimate, with sufficient accuracy, the temperature and the deflection

Fig. 20

of the wire without making actual measurements of either value. If for any reason greater accuracy is desired, the deflection may be measured by hanging a target on the wire close to the insulator at each end of the span. One form of target, shown in Fig. 20, consists of an iron strip with cross-marks of different colors corresponding to different deflections. This strip is hung from the wire by means of a hook, and when the lowest point of wire comes in line with the point corresponding to the deflection called for by the temperature at which the wire is strung, the line is tied to the insulator. The correct deflection is easily determined by the lineman sighting from one target to the other while the wire is being pulled up. Since aluminum cables are lighter and cheaper than copper cables of equal length and resistance, they are used on many of the long-distance transmission lines, as well as for railway feeders, electric-light feeders, and bus-bars.

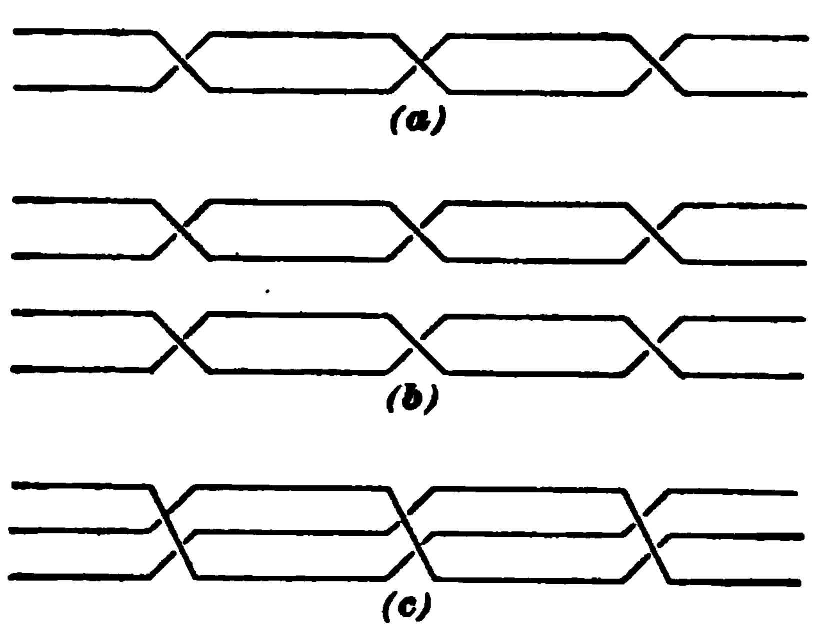


Fig. 21

23. Transposition of Transmission Lines.—When a number of alternating-current transmission lines are run side by side, the alternating magnetic field set up by the currents in one line may set up E. M. F.'s in the other lines,

thus causing unbalancing of the voltage and affecting the line drop. This disturbing action can be avoided by *transposing* or *spiraling* the wires so that the effect produced on one section of the line will be exactly counterbalanced by that produced in another. The most perfect example of spiraling is found in a cable where the conductors that make up the circuit are twisted together and the lines make a complete spiral every few inches. Such a cable has practically no inductive effect on a neighboring cable. Of course, in overhead transmission work, transpositions are not made very numerous because they make the wires harder to trace up in case of trouble and may, on high-pressure work, tend to promote crosses. In fact, some lines that work satisfactorily are not transposed at all. The Niagara lines are transposed in six sections between Niagara Falls and Buffalo, about 23 miles. Practice seems to differ greatly with regard to the frequency with which high-pressure lines should be spiraled. In some cases they are not spiraled at all; in other cases they are spiraled every 2 or 3 miles. Telephone lines, if strung on the same poles with transmission lines should be transposed every fourth or fifth pole, otherwise the telephones may be so noisy as to render conversation very difficult. Fig. 21 (*a*) shows

FIG. 22

the transposition of a single-phase line; (*b*) a two-phase line, and (*c*) a three-phase line. Fig. 22 shows a transposition on a high-tension, three-phase line, each wire being shifted around one pin, or one-third of a turn. Where transpositions

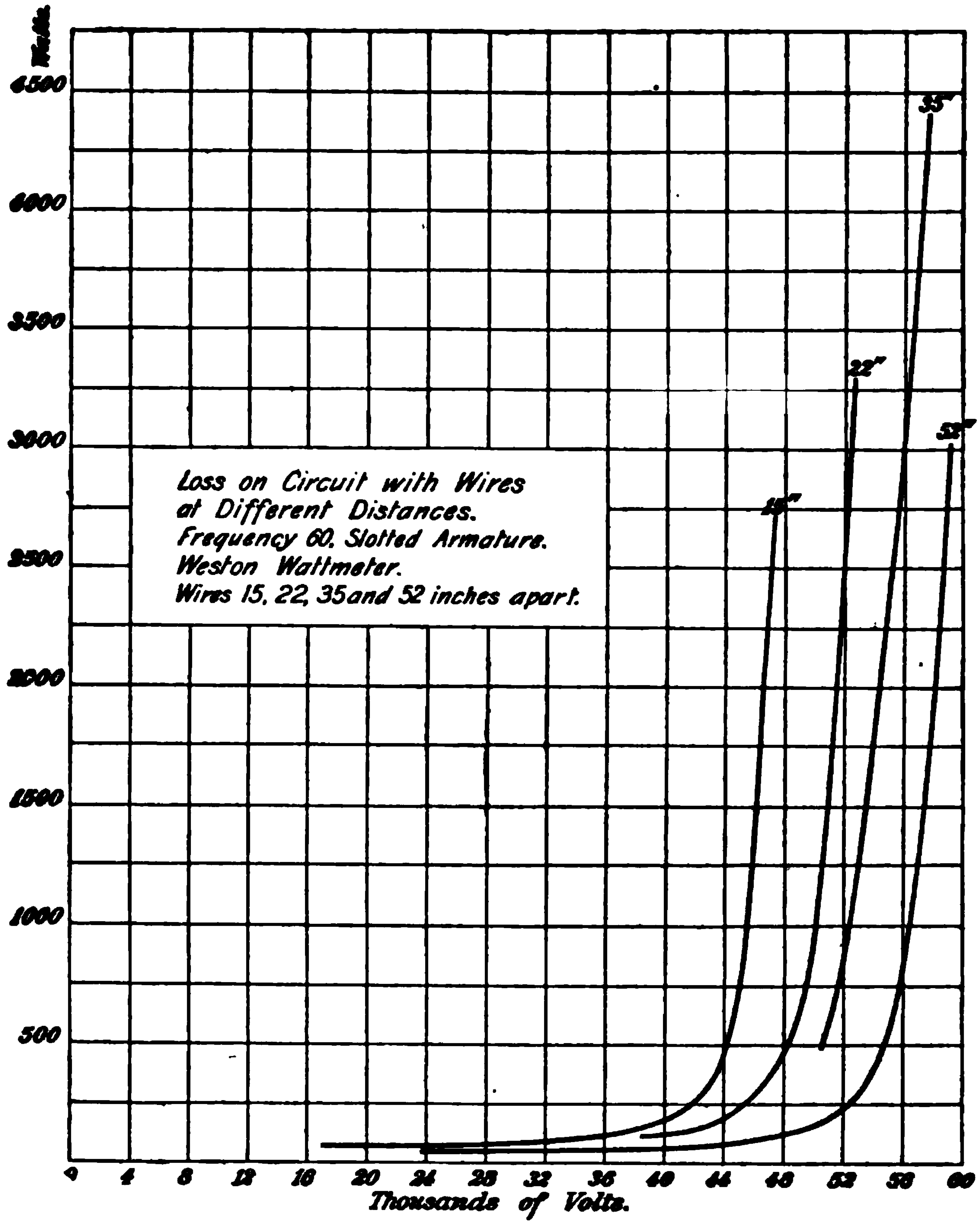


FIG. 23

are made in this way, it is advisable to place the pins on the cross-arms of each pole a little farther apart than the standard distance, so that the lines will not come too close together where they pass each other at the center of the span.

24. Leakage on High-Tension Lines.—On a high-tension line there is always some loss due to leakage, although if the lines be well separated and carefully insulated, this loss may be kept within reasonable limits. The leakage takes place between the wires either directly through the intervening air or over the insulators. When the pressure is raised to a high amount, a brush discharge takes place between the wires and the loss due to this discharge may be considerable, if the wires are not well separated. The curves in Fig. 23 show the results of some tests made by Mr. R. D. Mershon* to determine the relation between the loss, the pressure, and the distance between wires. These tests were made on a line about 2¼ miles in length. It is seen that there is a certain pressure, for each distance between wires, beyond which the loss increases very rapidly and that the nearer the wires are together, the lower the pressure at which the curves begin to rise rapidly. The loss by leakage at the insulators, of course, depends to a considerable extent on the design of the insulator, and also on its condition, i. e., whether wet or dry. It is difficult, therefore, to state very definitely what this loss is, but a number of measurements show that it is in the neighborhood of 2 watts per insulator for lines operated at 25,000 volts, and does not exceed 4 watts with a pressure as high as 44,000 volts.

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*Transactions American Institute of Electrical Engineers, Vol. XV.

UNDERGROUND CONSTRUCTION

25. In cities, it is necessary to place the wires underground, especially in the business districts. The best way to do this is to provide a regular tunnel, or *subway*, in which the various wires, or cables, can be placed and which will be large enough to allow a man to walk through for inspection or repair. This method is, however, very expensive and can only be used in a few very large cities. Another method is to use *conduits* through which to run the cables. These conduits usually consist of tubes of some kind that are buried in the ground and thus provide ducts into which the cables may be drawn. The ducts terminate in *manholes* usually placed at street intersections, by which access may be had to the cables and from which they may be drawn into or out of the ducts. A third method and one that has been largely used in cities for distributing current for lighting purposes, is to bury tubes containing insulated conductors in the ground. In this system the conductors cannot be withdrawn, as in the conduit system, and there is a separate tube for each set of conductors. The Edison tube system belongs to this variety, and a very large amount of lighting and power distribution on the three-wire, low-pressure system has been carried out by using underground conductors of this kind.

CONDUITS

26. A large variety of **conduits** are in use, and it has not been definitely settled as yet just which type is the best; but the following will serve to give an idea as to some of the more common forms that have stood the test of actual work and are in extended use.

27. Creosoted-Wood Conduit.—A form of conduit that was at one time largely used is composed of sections

of wooden tubing, the fiber of the wood being impregnated with creosote, in order to prevent its decay. This form of conduit is commonly known as **pump-log conduit.** A section of this conduit is shown in Fig. 24; the ends are doweled in order to preserve the proper alinement in joining. These sections are usually 8 feet in length, and have circular holes through their centers from $1\frac{1}{2}$ to 3 inches in diameter, according to the size of cable to be drawn in. The external cross-section is square and $4\frac{1}{2}$ inches on the side, in the case of a tube having a 3-inch internal diameter. Such a conduit as this, if properly impregnated with creosote, will probably have a life of from 15 to 20 years, and perhaps much longer, this point being one concerning which there is considerable argument and which, probably, time alone will decide. In some cases, difficulty has been experienced with creosoted-wood conduits on account of the creosote attacking the lead covering of the cables.

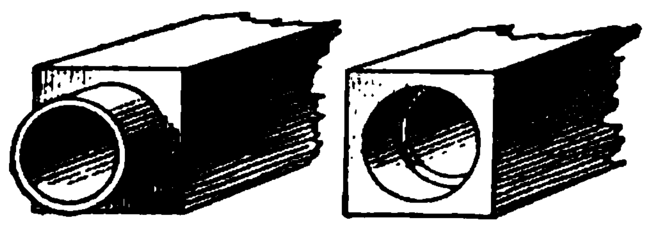


FIG. 24

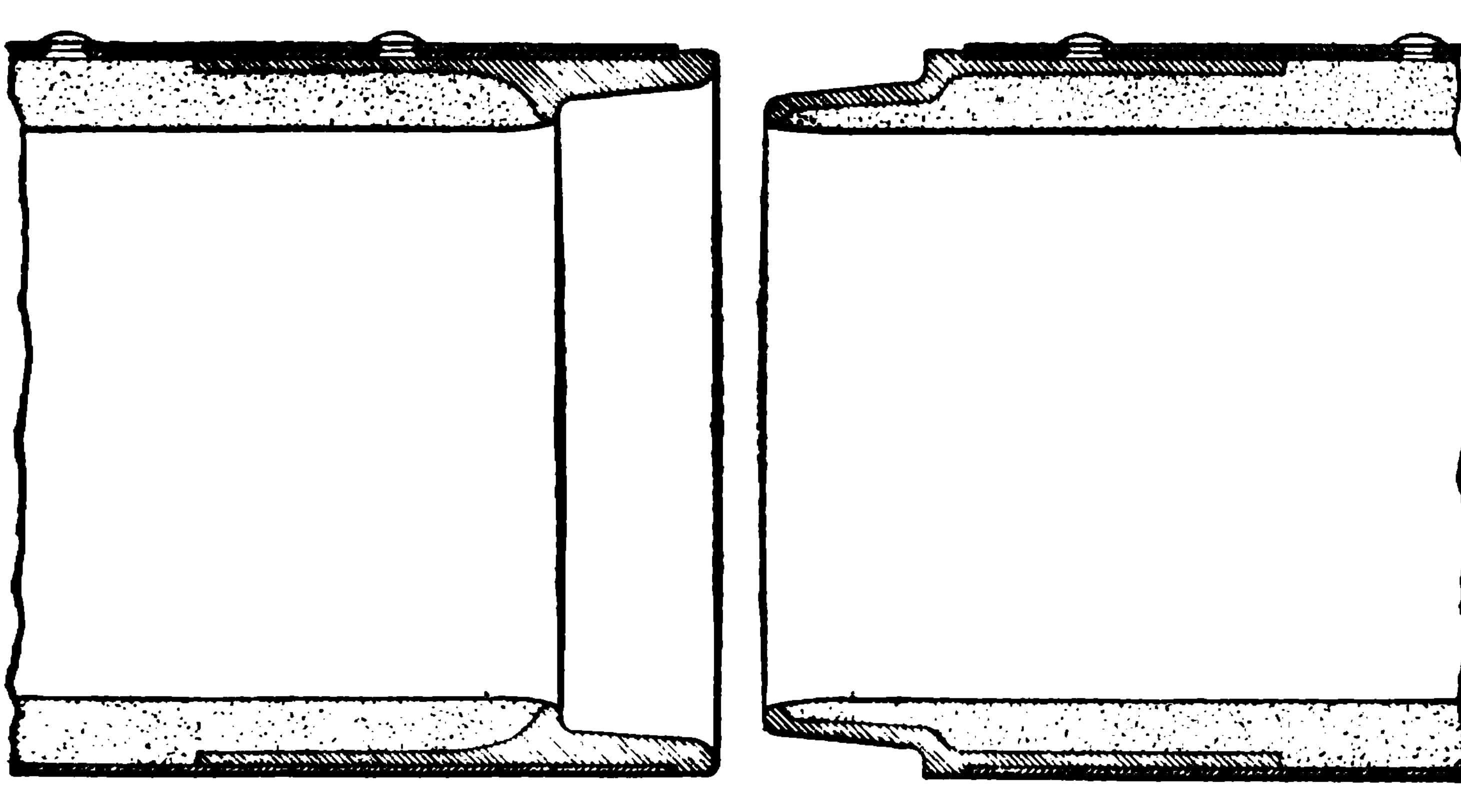


FIG. 25

28. Cement-Lined Pipe Conduit.—This conduit is made by the National Conduit and Cable Company. The sections shown in Fig. 25 are usually 8 feet long and are

made as follows: A tube is made of thin wrought iron, No. 26 B. W. G., .018 inch thick, and securely held by rivets 2 inches apart. The tube is then lined with a wall of Rosendale cement $\frac{5}{8}$ inch thick, the inner surface of which is polished while drying, so as to form a perfectly smooth tube. This tubing comes in three sizes, each having a length of 8 feet and internal diameters of 2, $2\frac{1}{2}$, and 3 inches, the latter being the standard size. Each end is provided with a cast-iron beveled socket joint, by the use of which perfect alinement may be obtained by merely butting the ends together. These beveled socket joints also allow of slight bends being made in the line of conduit as it is being laid.

FIG. 26

29. Vitrified-Clay or Terra-Cotta Conduit.—A form of conduit that is probably used in good construction work to a greater extent than any other is made of vitrified clay. This material has the advantage of being absolutely proof against all chemical action, and unless destroyed by mechanical means will last for ages. Besides this, its insulating properties are high and it is comparatively cheap and easily laid.

FIG. 27

Clay, or terra-cotta conduits are made in two general forms—multiple duct and single duct. Of the former type the most common is the 4-duct, two sections of which

are shown in cross-section in Fig. 26. They are also made with 2, 3, 4, 6, and 9 ducts.

30. The form of clay conduits now most commonly used is the single duct shown in Fig. 27; this is usually made in 18-inch lengths, has an internal diameter of from 3 to $3\frac{1}{4}$ inches, and is $4\frac{5}{8}$ inches square outside. This duct has a

FIG. 28

great advantage over the multiple-duct sections in the greater ease of handling and also in the fact that it is much less liable to become warped or crooked in the process of burning during its manufacture than the larger and more complicated forms. Like the cement-lined pipe, it is laid on a bed of concrete,

FIG. 29

cemented together with mortar, and enclosed on all sides and on top by concrete. In laying, a wooden mandrel, such as is shown in Fig. 28, 3 inches in diameter and about 30 inches in length, is used. At one end is provided an eye *a*, which

may be engaged by a hook, in order to draw it through the conduit, while at the other end is secured a rubber gasket *b* having a diameter slightly larger than that of the interior of the duct. One of these mandrels is placed in each duct when the work of laying is begun. As the work progresses, the mandrel is drawn along through the duct by the workmen,

FIG. 30

by means of an iron hook at the end of a rod about 3 feet long, the method of doing this being shown in Fig. 29. By this means, the formation of shoulders on the inner walls of the ducts at the joints is prevented, and any dirt that may have dropped into the duct is also removed. The cylindrical part of the mandrel insures good alinement of

the ducts, thus securing a perfect tube from manhole to manhole.

31. Fig. 29 illustrates the method of laying this conduit, and shows how the joints should be broken in the various layers so as to insure a maximum lateral strength to the structure. All conduits should be laid to such grades that there will be no low points or traps in the conduit that will not drain into the manholes.

FIG. 31

Figs. 30 and 31 show two arrangements of conduit used for distributing power from the Niagara Falls power station.* These are made of clay ducts laid in cement and covered, as shown, with concrete. The arrangement shown in Fig. 30 was used whenever the sewers were low enough to admit of good drainage, because it allowed a more convenient arrangement of cables in the manholes than the grouping shown in Fig. 31. Drainage was provided by the drain tiles *a*, *a*

*L. B. Stillwell, Transactions American Institute of Electrical Engineers, Vol. XVIII.

surrounded by loose gravel. These conduits are arranged so that there is never more than one duct between any duct and the ground, the object being to facilitate the dissipation of heat generated in the cables.

32. Bituminized-Fiber Conduit.—Another kind of conduit that has recently been introduced is made of fibrous material treated with bituminous compound in such a way as to make a hard, dense tube. This conduit is light, strong, impervious to moisture, and has high insulating properties. Joints are made by fitting the lengths together in the same way as the pump-log conduit. Before placing a length in position, the end is dipped in hot pitch, or similar compound, so that when the end is pushed in, a water-tight joint is formed. The ordinary size of this conduit is 3 inches inside diameter and it is made in 7-foot lengths. The wall of the tube is about $\frac{3}{8}$ inch thick. The conduit is usually laid in concrete, as described for the clay conduit, but owing to the nature of the joints it is not necessary to use mandrels if ordinary care is taken.

MANHOLES

33. Manholes form a very important part in cable systems and require careful designing to properly adapt them to the particular conditions to be met. They are usually placed about 400 feet apart, and, if possible, at the intersection of streets. They should be located with a view to making the line of conduit between them as nearly straight as possible. The size of the manhole will depend on the number of ducts that are to be led to it, as well as the number of men that will be required to work in it at one time. Manholes 6 feet square and from 5 to 6 feet high will usually be required for large systems, while for smaller systems, or the outlying portions of large ones, they may be made as small as 4 feet in length, in the direction of the conduit, 3 feet wide and 3 or 4 feet high.

Manholes may be constructed of either concrete or hard-burned brick laid in Portland-cement mortar. The foundation

should consist of a layer of concrete at least 6 inches thick. The walls, if of brick, should be laid in cement mortar, and should, also, be thoroughly plastered on the outside with the same mortar. They should never be less than 8 inches thick, and should be made double this thickness where large manholes are constructed in busy streets. As the brickwork is laid up, the supports for the iron brackets that hold the cables around the sides should be built in. The roof should

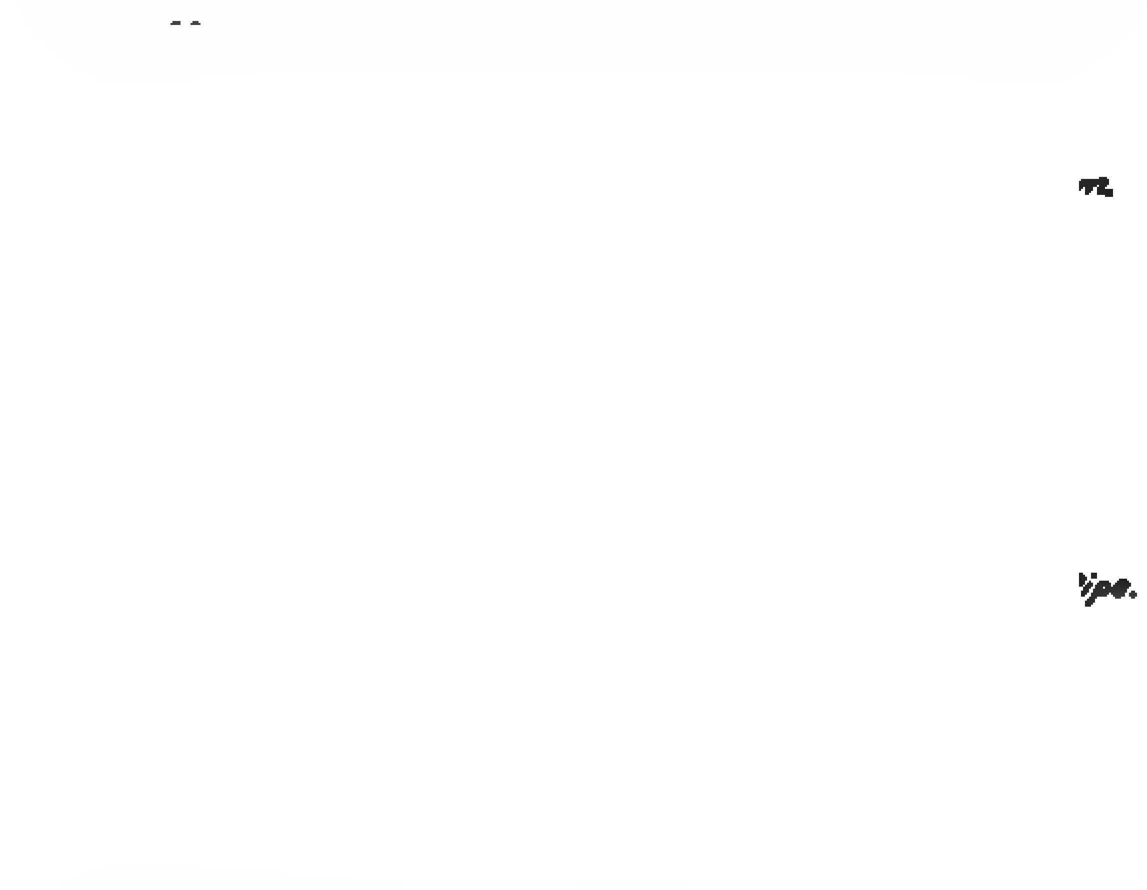


FIG. 32

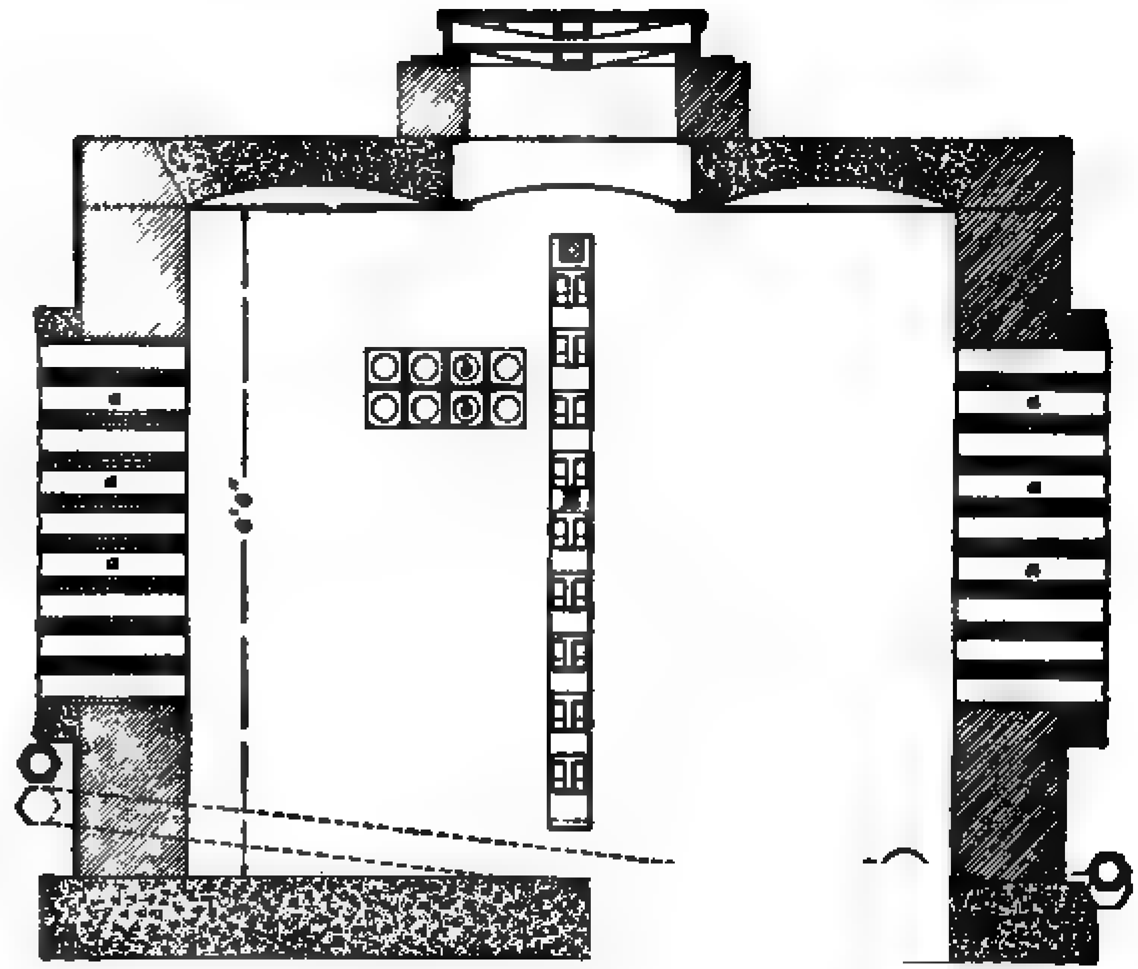
be of either arched brick, concrete, or structural iron, supporting some form of cast-iron manhole cover, of which there are several types on the market.

34. Fig. 32 shows a cross-section of a ventilated manhole well suited for ordinary power-distribution work. It has been found better, on the whole, to provide manholes with ventilated covers and good sewer connections than to close them up tight, as was formerly done. If they are tightly sealed, gases are liable to accumulate and cause explosions. In Fig. 32 the manhole is provided with two

sewer connections, so that in case the bottom one gets clogged up, the water will be able to flow through the side connection instead of backing up into the ducts. Both connections are provided with traps to keep out the sewer gas, and the bottom connection is equipped with a backwater valve to keep water from backing into the manhole. A removable cover is provided at the backwater valve, so that any dirt that accumulates can be cleaned out.

The roof of the manhole is made by laying 3″ × 3″ I beams across the top and filling between them with brick, the whole being covered with a layer of cement. The manhole cover may be either round or rectangular, the round type being preferred. Fig. 33 (*a*) and (*b*) shows two sectional views of the style of manhole used with the conduit shown in Figs. 30 and 31. The roof of this manhole is made of concrete arches supported by the side wall and by two I beams, as shown; *a*, *a*, *a* are the ducts of the main conduit, and *b*, *b* the ducts of the conduit through which the branch lines are taken. The cables pass around the side of the manhole, and are held in place on the racks *R*, *R*. The manhole is provided with a sewer connection at *S*, and the drains that run alongside the conduit also attach to the sewer connection, as shown.

35. Fig. 34 (*a*) shows an elliptical manhole made of concrete. This shape of manhole is becoming popular because it allows the cables to be easily bent to lie against the sides of the manhole. The rectangular corners of a square manhole are practically waste space, because the cables cannot be forced into these corners, or if the attempt is made to force them in, they are almost sure to be damaged. The elliptical form therefore utilizes the material to the best advantage. The main features of the construction are shown by the figure, so that little explanation is necessary. The main part *a* is of concrete, molded in a suitable form, and in this case the conduit *b* is of the 9-duct multiple type. The 2″ × 4″ timbers *c* are built into the concrete to form a base for the cable brackets. This manhole is comparatively small, so



(a) (b)

FIG 38

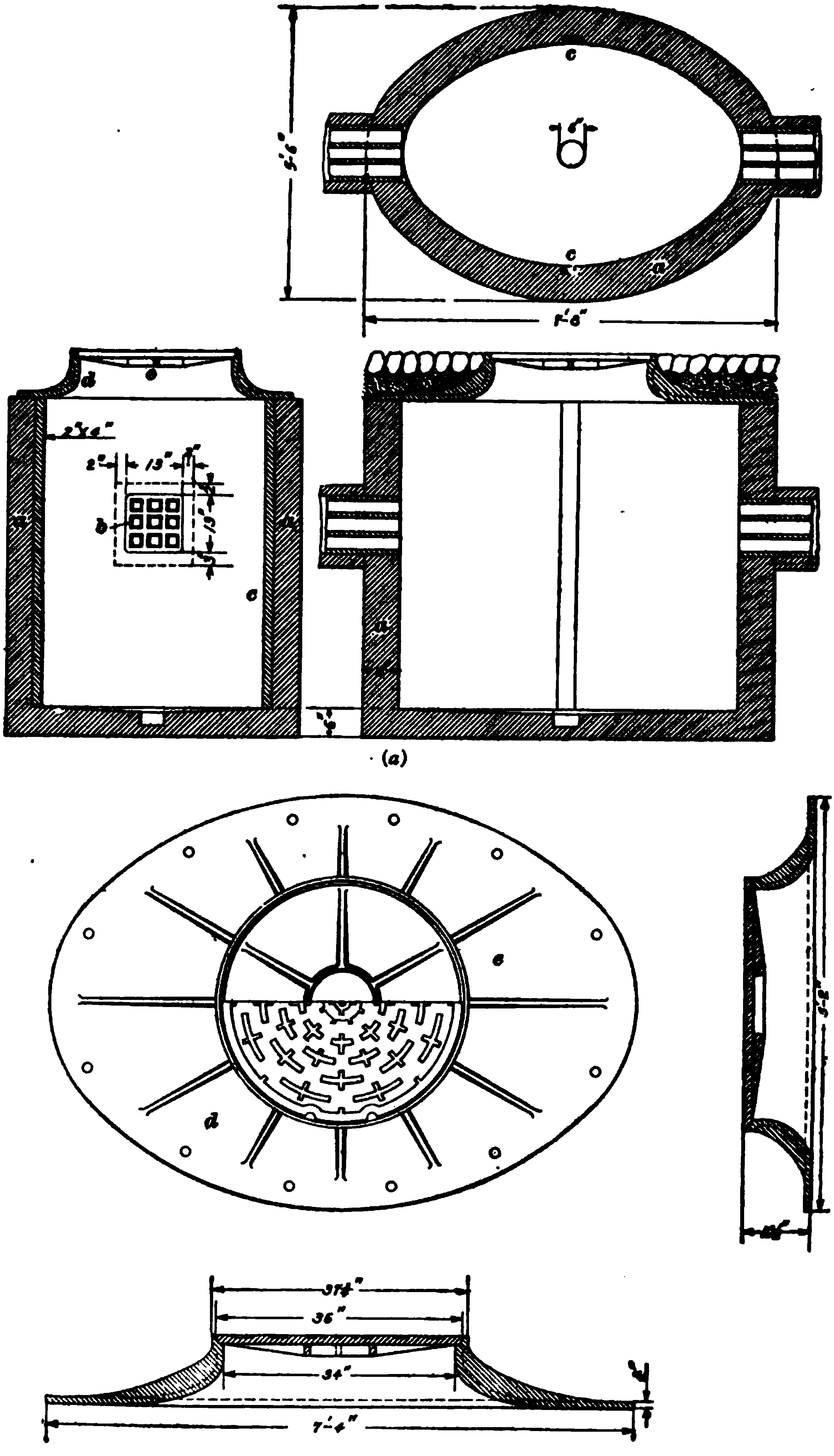


FIG. 34

that the holder *d* for the cast-iron cover *e*, forms the roof. This manhole, like nearly all those now constructed, is of the ventilated type. In case manholes are situated above the level of the sewer, the water that accumulates in them is usually removed by means of a water siphon. Fig. 34 (*b*) shows the cast-iron roof and cover.

36. After all work on the conduit and manholes has been completed, the cables are drawn into the ducts. In order to do this, it is necessary to have a wire or rope passing through the duct; this is introduced by the process called **rodding,** which consists in pushing a number of jointed rods into a duct from one manhole until the first rod reaches the other manhole. The rods are joined together by screw connections or bayonet joints, as they are pushed in. When the chain of rods reaches between the two manholes, a rope or wire is attached to one end and pulled through, the rods being disjointed one by one as they reach the second manhole.

The introduction of the wire into the duct may often be greatly facilitated by using, instead of the rods, a steel wire about $\frac{1}{4}$ inch in diameter and provided with a ball about 1 inch in diameter at its end. This wire may be pushed through a smooth duct without trouble for distances up to 500 feet. If an obstruction is found during the rodding that cannot be removed by means of the rods or by water, the distance to the obstruction can readily be measured on the withdrawal of the rod. The conduit should then be opened, the difficulty removed, and the structure repaired. This difficulty, however, should never be met when proper care is taken in laying the conduit.

37. Drawing In.—The process of **drawing in** the cable is illustrated in Fig. 35. The cable reel should be mounted on horses, so as to be free to revolve in such a manner that the cable will unwind from its top. The end of the rope leading through the duct should then be attached to the cable by grips made specially for the purpose or by binding it with iron wire for a distance of 18 inches or 2 feet

from the end. Fig. 35 (*b*) shows a section of a cable grip of iron pipe made to fit the cable snugly.. It is fastened to the cable, as shown, by common wood screws, and the piece *d* to which the drawing-in rope is fastened is screwed into the end of the iron pipe. Another form of cable grip is shown

(*a*) (*b*)

Fig. 35

in Fig. 36. Whenever a hole is made in the end of the cable for fastening the drawing-in rope, the end should be cut off when the cable has been drawn in, the moisture driven out, and the end sealed if a joint is not to be made at once. The other end of the rope is passed over the grooved rollers, arranged on heavy planks mounted in the distant manhole, as shown, and is secured to a capstan or some form of windlass, by which a slow and steady pull may be exerted.

Fig. 36

A man should be stationed in the manhole at which the cable enters to properly guide the cable into the duct, to prevent it from being kinked or unduly strained. It is well to use a special funnel-shaped guide, made of wood or lead, at the entrance of the duct, in order to further insure the cable against injury by the corners of the duct. This guide

is shown in Fig. 35 (*a*). It is sawed longitudinally into two sections, as shown in the left part of Fig. 35 (*a*), where the cable is to continue on through a manhole and where it would therefore be impossible to remove the cylindrical protector were it not sawed in two. Fig. 37 shows another arrangement for drawing in cables. In this case the windlass is arranged vertically in the manhole itself.

DISTRIBUTION FROM MANHOLES

38. Cables.—The construction of the **cables** themselves depends on the kind of service to which they are to be put. Two kinds of insulation are available—rubber and paper. With good rubber insulation, a small puncture in the lead sheath may not impair the insulation for some time, because the rubber is, to a large extent, proof against moisture. On the other hand, paper insulation will be damaged if the lead sheath becomes punctured so as to admit moisture. Paper insulation is, however, cheaper than rubber, and if the cables are carefully installed will give excellent service. Fig. 38 shows a paper-insulated cable designed for 6,600-volt, three-phase transmission. The three conductors are insulated with paper wrapping to a thickness of $\frac{1}{8}$ inch. These three strands are then twisted together and covered with a wrapping of paper $\frac{1}{16}$ inch thick, over which the $\frac{1}{8}$-inch lead covering is forced. The paper is treated with insulating compound and the space between the strands, shown black in the figure, is filled with jute treated with insulating compound.

39. Underground cables have been regularly operated in America at a pressure of 25,000 volts. These cables were made for the St. Croix Power Company, and both paper-insulated and rubber-insulated cables were installed, the construction of the cables being similar to that shown in Fig. 38. The paper insulation on each conductor is $\frac{9}{32}$ inch thick, and the outside paper jacket is $\frac{4}{32}$ inch thick. In the rubber cable, the insulation on each conductor is $\frac{7}{32}$ inch thick, and the jacket surrounding the

conductors is $\frac{5}{32}$ inch thick. The sheath is of lead with 3 per cent. of tin added.

40. Junction Boxes.—In underground electric-power distribution, it is important to have the various parts of the system so arranged that they can be disconnected, if necessary, because faults are liable to develop, and if the various sections can be readily disconnected, it makes the location of the defective portion very much easier to find; also, when

Fig. 37

the defective part is located, it can easily be cut out without interfering with the operation of the remainder of the system. Again, at a manhole or other distribution center, where a number of distribution cables are connected to the main

feeders running to the power station, it is necessary to insert fuses, so that any branch will at once be cut off from the main cables in case of an overload, short circuit, or other defect giving rise to a rush of current. On low-pressure networks, the distribution cables are attached to the main cables, or feeders, by means of *junction boxes*, which are provided with suitable fuse terminals. Junction boxes are made in a

Fig. 38

great many different styles, but they are usually in the form of cast-iron boxes, containing suitable fuse-contact terminals and arranged so that they can be fastened to the side walls or roof of the manhole. These boxes must of course be water-tight.

41. Fig. 39 shows a typical junction box designed for fastening to the side walls or roof; it is known as a *four-way box*, because it accommodates four positive and four negative branch cables; it is designed for use on low-pressure, three-wire work. A and B are the positive and negative bars, which are made of copper and are well insulated from each other. These bars are connected to the cable terminals through copper fuses f, so that in case a short circuit occurs on a line, the fuses will blow and thus prevent damage. The short neutral bar shown in the bottom of the box attaches directly to the cables, because it is not usually considered necessary or even desirable to place a fuse in the neutral. The small wires p, p are *pressure wires* that run back to the station and there connect to the voltmeter, so that the voltage at the center of distribution, represented by the

junction box, may be determined at any time. These pressure wires are protected by fuses placed in the small fuse receptacles *b*, *b*, *b*. Each pressure wire connects to one side of a cut-out *b* and the other sides connect to the +, −,

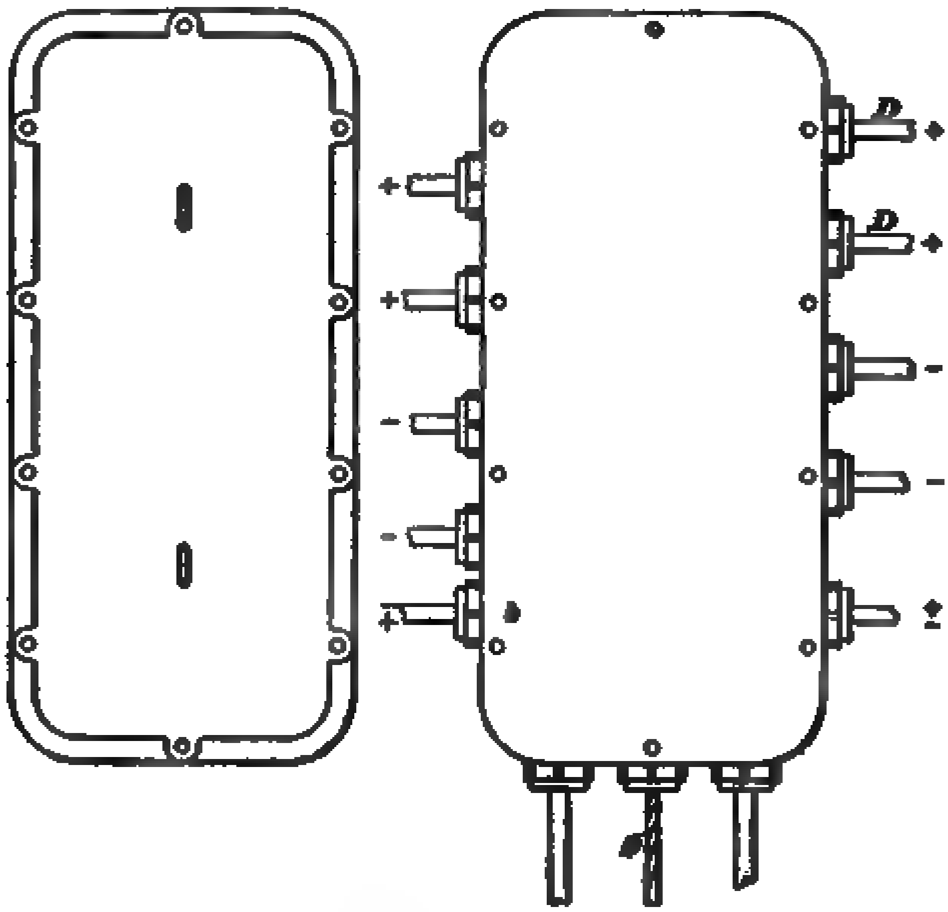


Fig. 39

and neutral bars. The cables pass into the box through water-tight rubber gaskets, and the box is closed by a water-tight cover.

Fig. 40 shows a recent type of junction box made by the General Electric Company. This differs considerably from those of the ordinary type, as it is designed to be placed in the roof of the manhole and access gained to it from the street. In many manholes there is very little room for placing junction boxes on the side walls without interfering with the cables, and moreover manholes are sometimes filled with gas or water so that it is a difficult matter to get at the boxes to replace fuses or disconnect defective cables. Fig. 40 (*a*) is an exterior view of the box and (*b*) shows it

located in a manhole. All cables enter through the bottom, the lead sheath being joined to a nozzle by means of a wiped joint and the nozzle secured against the box by means of a union, as shown, thus making a joint that is gas- and water-tight, yet easily connected or disconnected. Fig. 40 (*c*) shows the arrangement of the fuses. The main cables connect, through fuses, to the castings *a*, *b*, *c* and the branch cables are connected to these through fuses *d*, *e*, etc. The box

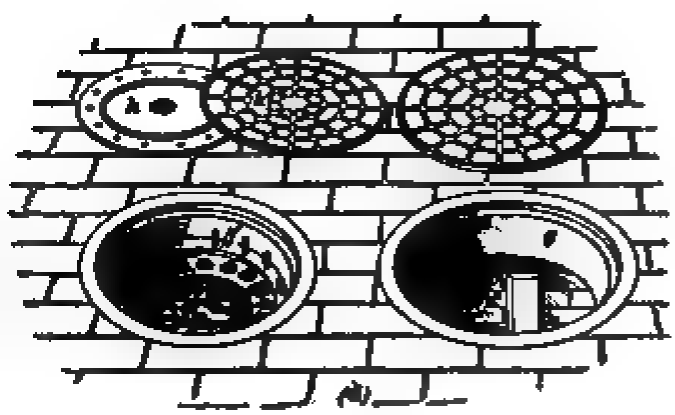


FIG. 40

is intended for a three-wire system and *1*, *2*, *3* are small blocks to which the pressure wires are connected. In Fig. 40 (*d*), the location of the junction box *f*, with reference to the manhole opening *g*, is shown. The junction box is made water-tight by means of the inner cover *h*, which is screwed down against a gasket. After the box is installed, a small hole is made close to the inner cover and opening into the manhole; this prevents any great accumulation of water

between the inner and outer covers, so that there is little tendency for the gasket to leak. The junction box is covered by a loose cover *k* similar to that used for the manhole. If desired, the lower part of the box can be filled with oil, similar to that used in transformers; this is advisable with paper-insulated cables, as the oil will prevent moisture from working its way into the insulation.

42. **Service Boxes.**—When the conduit system of distribution is used, and where customers have to be supplied, small *handholes* are provided wherever distributing points may be necessary. These are much smaller and shallower than manholes and only run down as far as the conduit. In these handholes a **service box** is placed. Fig. 41 shows

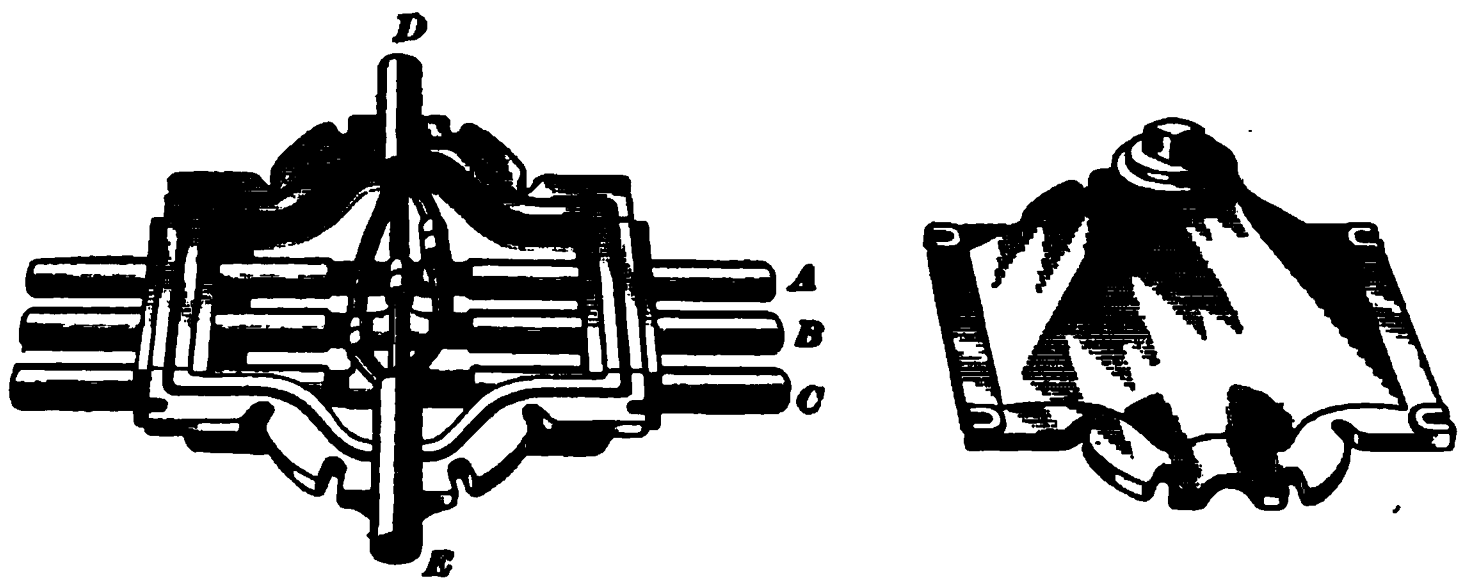


FIG. 41

one style of service box with its cover removed. *A*, *B*, and *C* are the main cables that run straight through the box without being cut. *D*, *E* are the three-wire branch-service cables, or tubes, for supplying current to the buildings. These are attached to the main cables by means of suitable clamps, and after the cover is bolted in position the box is filled with insulating compound. Fig. 42 shows another style of service box for use on the three-wire system. In this four-way box the main cables are fastened to terminals instead of passing straight through. Fig. 43 shows a handhole with its service box arranged for delivering current to overhead conductors. The main feeders, running from manhole to manhole, are placed in the lower tiers of conduits, and the service mains

that run back from the manholes are run in the upper row, so that they will be accessible for the connection of service boxes.

43. Joining Cables.—For low-pressure work, cables are usually joined in the manholes by means of coupling boxes or junction boxes. Sometimes, however, joints must be made without the use of these boxes, in which cases the job must be very carefully done.

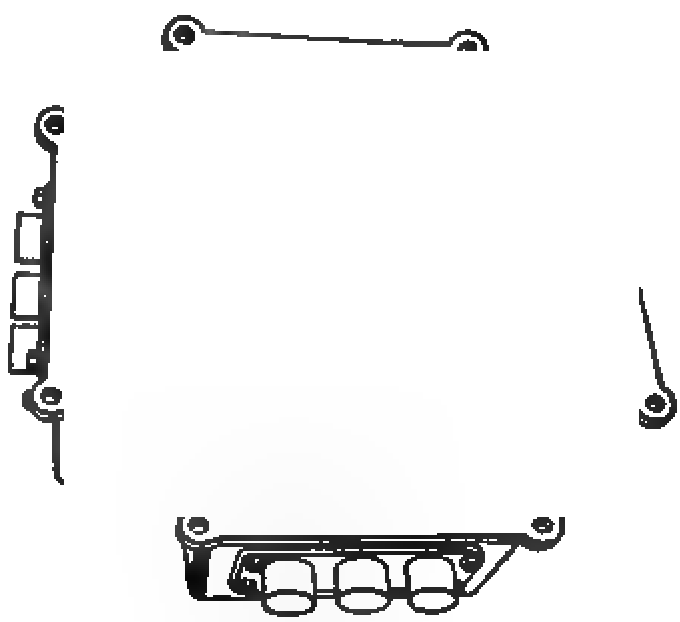


FIG. 42

First, the soldered end of the cable is cut off and the cable carefully examined for moisture. If a little moisture be present and there is still more than enough room for the joint, it is allowable to cut off another short length. If indications of moisture are still present, heat should be applied to the lead covering, starting from a distance and proceeding along the cable to the end. Thus, the moisture is driven out at the cut. When the use of torches is not allowed on account of gas in the manholes, hot insulating compound, such as boiling paraffin, may be poured over the cable. This process is known as boiling out. To ascertain whether moisture is present, the piece last cut off is stripped of its lead covering and plunged into hot insulating compound. If bubbles rise, moisture is still present.

44. High-Tension Cable Joint.—Fig. 44 shows a typical **high-tension cable joint.** After all moisture has been driven out, the lead sheath is cut off for a suitable distance from each end and the cable insulation is also cut back as indicated. A piece of lead pipe A of considerably larger diameter than the cable and a little longer than

the total length of sheath stripped off is then slipped back on the cable. A copper sleeve (*b*) connects the abutting ends of the cable, and is sweated in place with solder worked in through the slot in the top of the sleeve. The sleeve is then covered with tape until it is brought up to a level with the cable insulation and a paper insulating sleeve *c* that has previously been slipped back over the cable insula-

Fig. 43

tion is placed over the joint and held there by a wrapping of string. The lead sleeve is now slipped into place and the ends hammered down around the cable sheath as indicated, and then soldered to the sheath with a plumber's wiped joint. These joints should be very carefully made so that there will be no opportunity for moisture to work into the cable and thus cause a breakdown. Two V-shaped openings are made in the top of the sleeve by cutting the lead and turning it back, as shown in (*c*); through one of these hot insulating compound is poured until the joint is filled. One

of the openings allows the air to pass out while the compound is poured in at the other. In joining high-tension cables, the greatest care must be taken to have the joint perfect in every

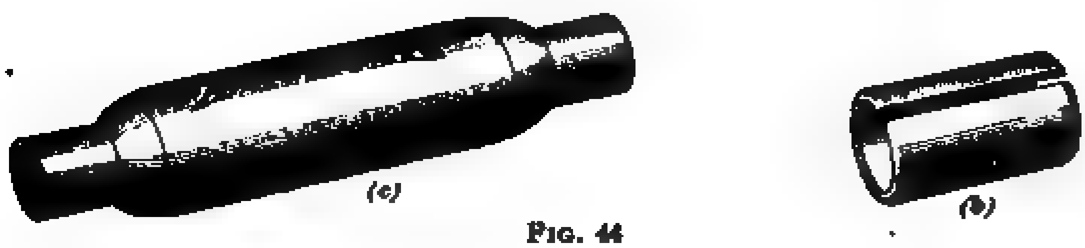


Fig. 44

particular. A slight defect may lead to a serious breakdown after the cable has been in use a short time.

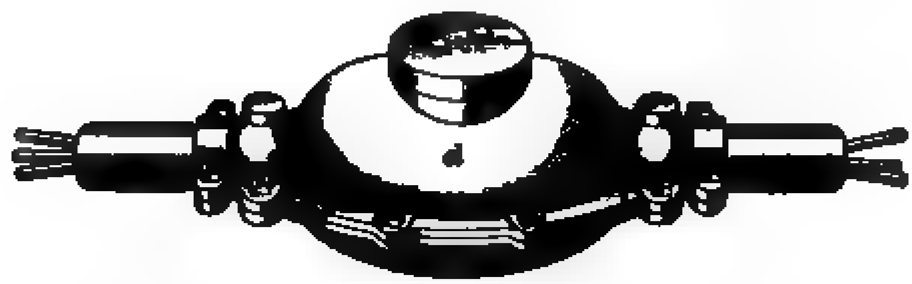
EDISON UNDERGROUND-TUBE SYSTEM

45. The **Edison underground-tube system** differs from the conduits previously described in that the conductors are placed in iron tubes that are buried in the ground. The conductors are, therefore, not removable. This arrangement has been used extensively for three-wire 110-220 volt distribution in the larger cities. The conductors themselves are usually in the shape of round copper rods; the main tubes are designed for use on the three-wire system and are, therefore, provided with three rods, as shown in the section in Fig. 45. Each rod is wound with an open spiral of rope that serves to keep the rods separated in case the insulating material in the tubes should become soft. After

Fig. 45

the rods have been provided with the rope spiral, they are bound together by means of a wrapping of rope and inserted in the iron pipe, the rods projecting for a short distance at each end. The whole tube is then filled with an

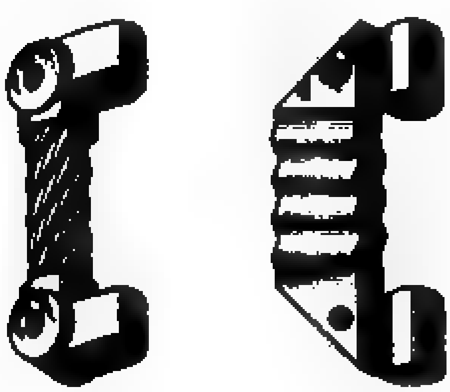
(a)



(b)

FIG. 46

insulating compound that becomes hard when cold. The tubes are made in 20-foot lengths and are laid in the ground about 30 inches below the surface of the pavement. They are joined together by means of the coupling boxes shown in Fig. 46 (*a*) and (*b*). Fig. 46 (*a*) shows the lower half of the box only, with the main tubes entering each end. The conductors are connected together by means of short, flexible, copper cables *c*, *c*, *c*, provided with lugs *b*, *b*, that fit over the rods and are soldered in place. A cover *d* similar to the lower half *e* is then placed in position and the two securely bolted together by means of flange bolts, as shown in (*b*). After this has been done, melted compound is poured through an opening in the upper casting and the joint is complete. Fig. 47 shows two styles of connectors used for connecting the ends of the rods; (*a*) is a stranded



(a) (b)

FIG. 47

copper cable with terminals, and (*b*) is a laminated copper connector. Fig. 48 indicates a length of pipe with a coupling.

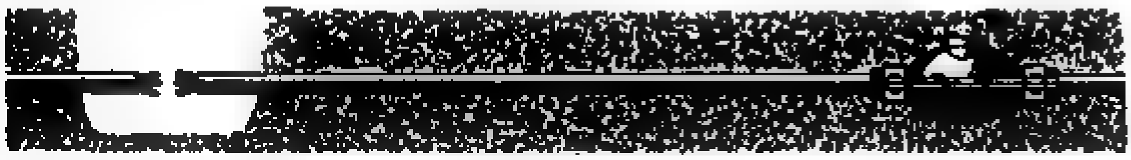


Fig. 48

46. Where branches are taken off the mains, T coupling boxes are used, as indicated in Fig. 49. This box, also, is filled with insulating compound that soon becomes hard and prevents the flexible connections from coming in contact with one another. At the centers of distribution (usually a

street intersection) junction boxes are provided; these correspond to the manholes of the conduit system. The main supply wires, or feeders, run from the station to these junction boxes, whence the mains are run to the various districts

where light or power is supplied. Fig. 50 shows one of these junction boxes. The tubes enter at the lower part of the cast-iron box, and the mains are connected to the feeders through fuses that bridge over between the rings shown at the top. These fuses must be proportioned according to the size of the conductor in the tube to which they are

Fig. 50

connected. The allowable carrying capacities of underground tubes and cables have been made the subject of a large number of tests by the manufacturers, who furnish tables giving the limit to which their cables or tubes may be loaded with safety. The junction box shown in Fig. 50 is made water-tight by clamping down the cover by means of the

studs *b*, *b*, and the whole is then covered with a cast-iron plate resting in the groove *c* and coming flush with the street surface.

47. The underground tubes and fittings are rather expensive, but they are comparatively cheap to install, as all that is necessary is to dig a shallow trench and lay the tubes in the ground. This system has the disadvantage that if any trouble occurs it is somewhat awkward to get at

TABLE XI

CARRYING CAPACITY OF UNDERGROUND TUBES

Size of Each Conductor Circular Mils	Maximum Current in Each of Two Conductors
41,000	100
80,000	200
100,000	235
120,000	260
150,000	295
200,000	350
250,000	400
300,000	450
350,000	495
400,000	540
450,000	580
500,000	620

it, as the conductors cannot be pulled out as in a conduit system. When trouble occurs, the usual method of procedure is to dig a hole at one of the couplings and separate the ends. By making a few breaks in this way at different points, the section in which the ground or short circuit is present can soon be located and the defective length of tube removed. Another and quicker method of locating grounds will be described later.

48. The Edison tube system is not now used as largely as it once was for the main distributing lines or feeders. The present practice is to carry the main conductors from the station to the various distributing points in ducts, so that they may be drawn out if necessary. The tube system is, however, well adapted for the distributing mains, and is largely used for this purpose, because it allows service connections to be made easily and cheaply. Table XI gives the cross-section of the rods used in the standard tubes that are now used for distributing mains. Each tube has three conductors of the same size, and the table shows the allowable current when two of the conductors are loaded. If the system is balanced, the third wire will carry but a small current.

TESTS

49. In testing lines or apparatus, it is frequently necessary to make rough tests that will show whether or not circuits are continuous, broken, crossed, grounded, or properly insulated. These tests do not require accurate measurements; they are merely made for the purpose of determining the existence of a faulty condition.

50. **Magneto Testing Set.**—The most common, and probably, all things considered, the most useful, form of testing instrument for rough testing is that consisting of a magneto generator and bell mounted compactly in a box provided with a strap for convenience in carrying.

TESTING LINES FOR FAULTS

51. **Faults** on a line may be of two kinds: the line may be entirely broken, or it may be unbroken but in contact with some other conductor or with the ground. The former fault is termed a *break;* the latter a *cross*, or *ground*. A **break** may be of such a nature as to leave the ends of the conductor entirely insulated, or the wire may fall so as to form a cross or ground. A **cross** or **ground** may be of such

low resistance as to form a short circuit or it may possess high resistance, thus forming what is called a *leak*. There are a number of different methods used for locating faults, and as those most suitable depend to a considerable extent on the kind of work for which the lines are used, most of the points relating to testing will be left until the different subjects with which they are connected are considered.

52. Continuity Tests.—In testing wires for continuity, the terminals of the magneto set should be connected to the terminals of the wire and the generator operated. A ringing of the bell will usually indicate that the circuit is continuous. This is a sure test on short lines, but should be used with caution on long lines and with cables, because it may be that the electrostatic capacity of the line wires themselves will be sufficient to allow enough current to flow through the ringer to operate it, even though the line, or lines, be open at some distant point.

53. Testing for Crosses or Grounds.—In testing a line for crosses or grounds, one terminal of the magneto should be connected to the line under test, both ends of which are insulated from the ground and from other conductors. The other terminal of the magneto set should be connected successively with the earth and with any other conductors between which and the wire under test a cross is suspected. A ringing of the bell will, under these conditions, indicate that a cross exists between the wire under test and the ground or the other wires, as the case may be, and the strength with which the bell rings, and also the pull of the generator in turning, will indicate, in some measure, the extent of this cross.

54. Here, however, as in the case of continuity tests, the ringing of the bell is not a sure indication that a cross exists if the line under test is a very long one. The insulation may be perfect and yet permit a sufficient current to pass to and from the line through the bell to cause it to ring, these currents, of course, being due to the static

capacity of the line itself. In testing very long lines or comparatively short lines of cable, the magneto set must be used with caution and intelligence on account of the capacity effects referred to. For short circuits in local testing, however, the results may be relied on as being accurate.

Magneto testing sets are commonly wound in such manner that the generator will ring its own bell through a resistance of about 25,000 ohms. They may, however, be arranged to ring only through 10,000 ohms, or where especially desired, through from 50,000 to 75,000 ohms. The first figure mentioned—25,000 ohms—is probably the one best adapted for all-round testing work.

CURRENT DETECTOR GALVANOMETER

55. In order to test for grounds, crosses, or open circuits on long lines or on cables, without the liability to error that is likely to arise in testing with a magneto set, a cheap form of galvanometer for detecting currents, called a **detector galvanometer,** may be used. In testing for grounds or crosses, the galvanometer should be connected in series with several cells of battery and one terminal of the circuit applied to the wire under test, it being carefully insulated at both ends from the earth and from other wires, while the other terminal of the galvanometer and batteries should be connected successively to the ground and to adjoining wires. A sudden deflection of the galvanometer needle will take place whenever the circuit is first closed, this being due to the rush of current into the wire that is necessary to charge it. If the insulation is good, the needle of the galvanometer will soon return to zero; but if a leak exists from a line to the ground or the other wire with which it is being tested, the galvanometer needle will remain permanently deflected.

In testing for continuity, the distant end of the line should be grounded or connected with another wire that is known to be good, and the galvanometer and battery applied, either between the wire under test and the ground or the wire

under test and the good wire. In this case, a permanent deflection of the galvanometer needle will denote that the wire is continuous, while if the needle returns to zero it is an indication of a broken wire.

56. Test for Insulation Resistance.—One thing that it is important to know about lines is the state of their insulation. In order to determine this, measurements of the insulation resistance between the line and ground must be made, and if this resistance is found to be dangerously low, the trouble should at once be looked up and remedied. One of the most convenient methods for measuring insulation resistance is by means of a good high-resistance voltmeter. The voltmeter is much easier to handle than a reflecting

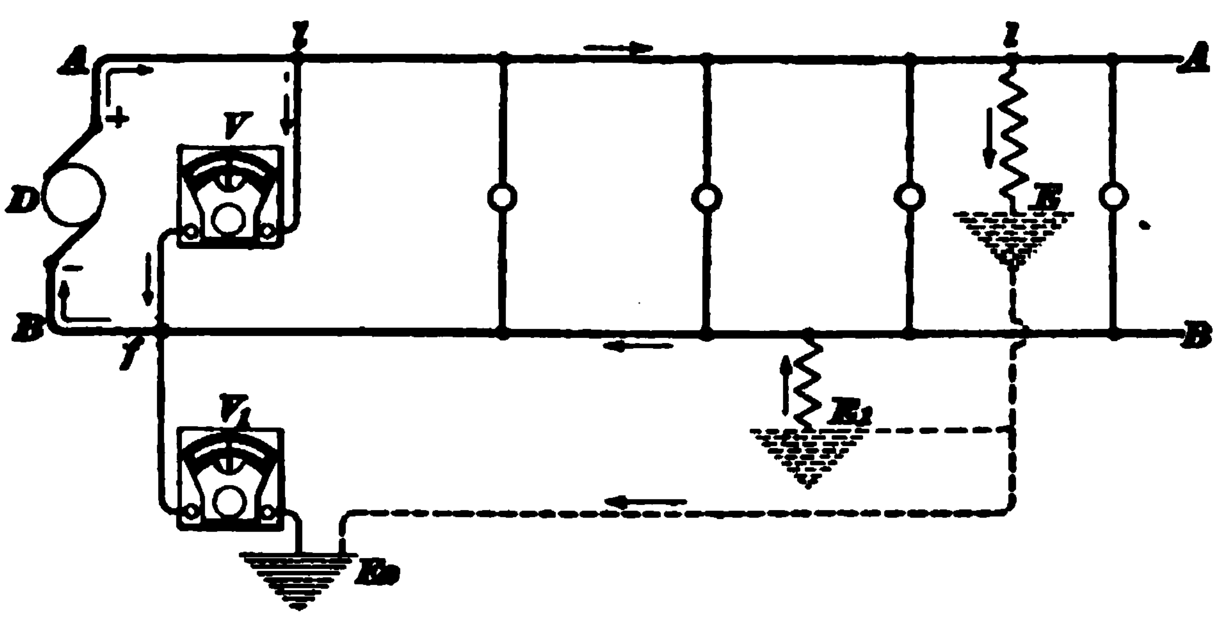


Fig. 51

galvanometer, and if the resistance of the voltmeter is known, insulation resistance measurements may be made with very little trouble. Suppose in Fig. 51 we wish to measure the insulation resistance of the line *A A*. The voltmeter is first connected across the lines at *V* in the usual manner and the voltage of the dynamo *D* obtained. Call this reading *V*. After taking the reading *V*, the voltmeter is connected between the line *B B* and the ground, as shown at V_1, and a reading V_1 obtained. In this case the current passes through the insulation from *l* to *E*, through the ground to E_2 and thence through V_1 to *f*. It is evident that if the insulation resistance of the line *A A* is very high, very little current will flow through the voltmeter,

and a small deflection will be the result. If the resistance r of the voltmeter is known, then the insulation resistance of the line will be

$$R = \frac{(V - V_1) r}{V_1} \qquad (3)$$

EXAMPLE.—The insulation resistance of an electric-light main was tested by means of a Weston voltmeter having a resistance of 18,000 ohms. When connected across the lines, the voltmeter gave a reading of 110 volts. When one line was connected to ground through the voltmeter, the reading was only 4 volts. What was the insulation resistance of the other line?

SOLUTION.—We have by formula 3,

$$R = \frac{(110 - 4)\ 18,000}{4} = \frac{106 \times 18,000}{4} = 477,000 \text{ ohms. Ans.}$$

NOTE.—The insulation resistance of lines is usually expressed in megohms, 1 megohm being equal to 1,000,000 ohms. The resistance of the line in this case would therefore be .477 megohm.

TESTS FOR GROUNDS OR CROSSES

57. Varley Loop Test.—One of the most common methods for locating a ground or cross is by means of the **Varley loop test.** In Fig. 52, G is a sensitive galvanometer connected across the arms of a Wheatstone bridge in the ordinary manner; $A\,B$ and $A\,C$ are the ratio arms and $C\,D$

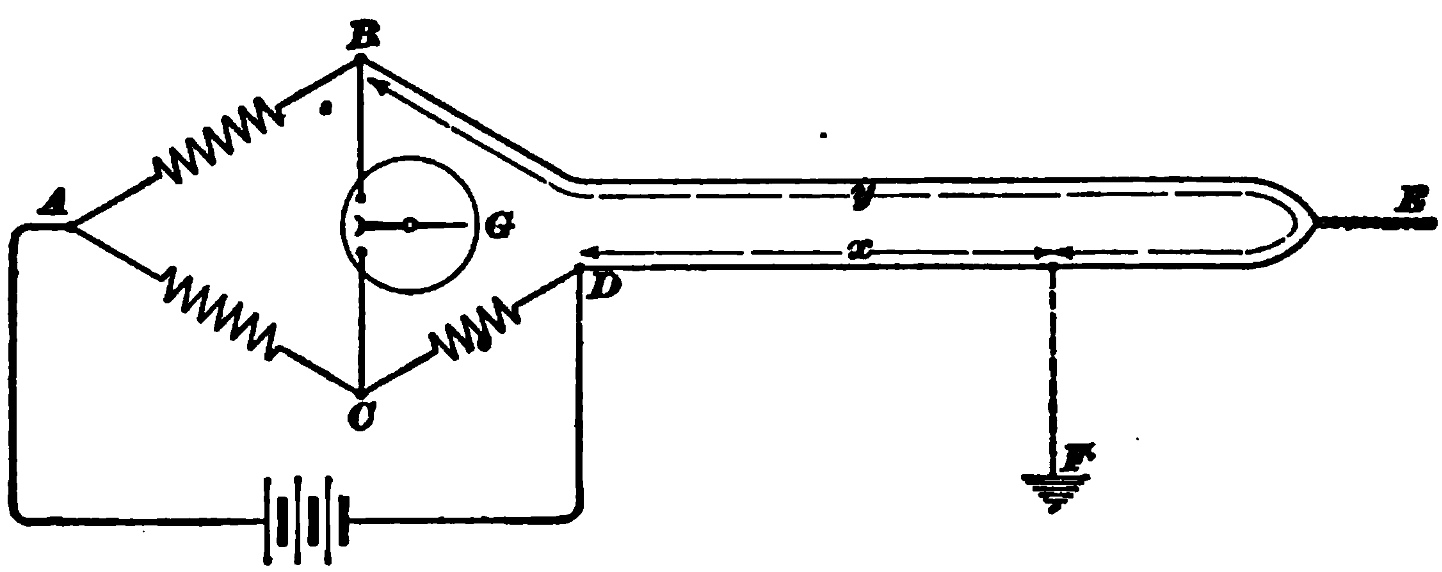


FIG. 52

the rheostat or balance arm of the bridge; $D\,E$ is the faulty line, $B\,E$ a good line, and F is the location of the fault. The two lines should be connected together at E and the ends of the loop $B\,E\,D$, so formed, connected across the terminals of the bridge as the unknown resistance. Call y the resistance

of the loop from B to F and x the resistance from D to F. With the battery connected between A and D, as in the ordinary method of using the Wheatstone bridge, balance the bridge. This will give, by working out the unknown resistance in the usual manner, a resistance R equal to the sum of the resistances of the two wires forming the loop; that is, $R = y + x$. Or, the resistance R of the whole loop may be calculated, if the length and size of the line wire are known.

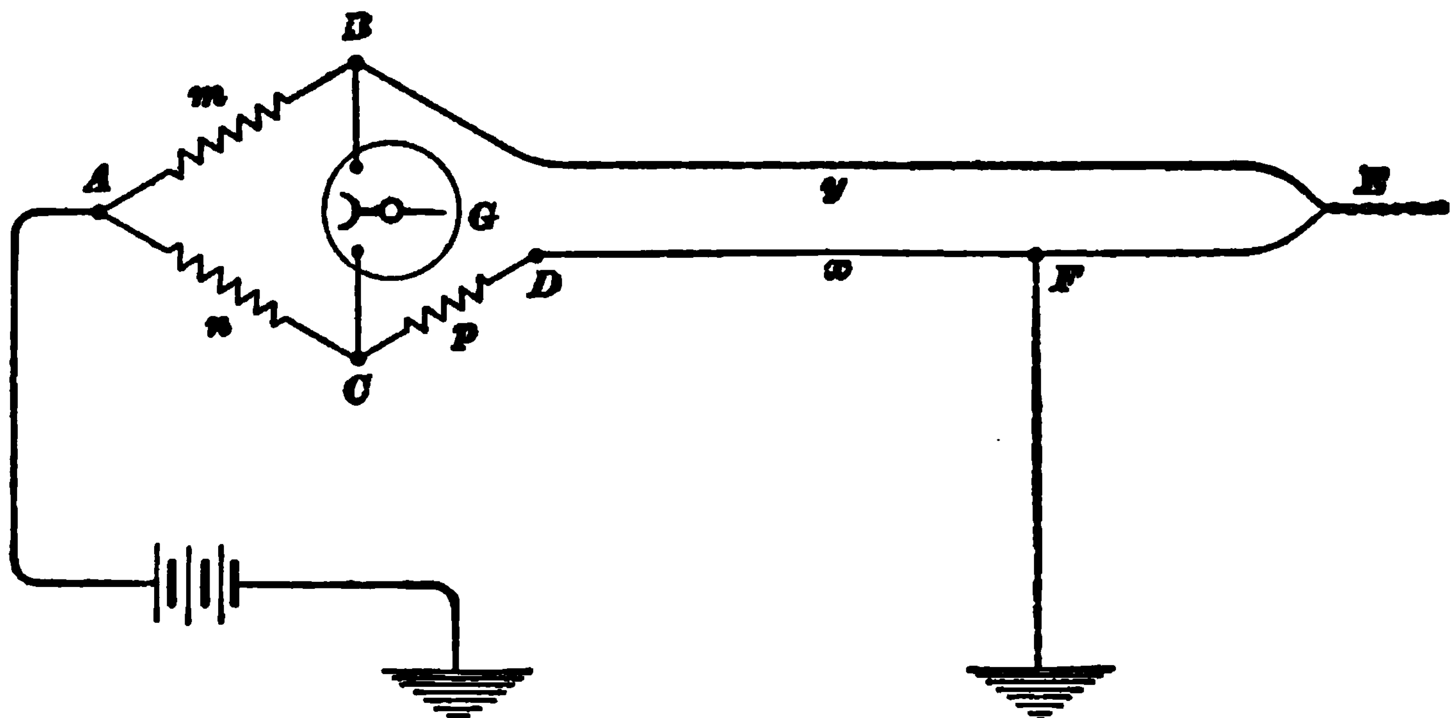


FIG. 53

Now disconnect the battery from D and connect it to the ground, as shown in Fig. 53. Then balance the bridge again, and the resistance x may be obtained by means of the following formula:

$$x = \frac{nR - mp}{m + n} \qquad (4)$$

in which m, n, and p are the values of the resistances in the arms $A\,B$, $A\,C$, and $C\,D$. After obtaining the resistance x from D to the fault F along the line $D\,E$ by means of formula 4, the distance (in feet or miles) from the testing end D to the fault F may be obtained by dividing this resistance x by the resistance of a unit length (a foot or a mile, as the case may be) of the line wire $D\,E$. The result obtained by this test is independent of the resistance at the fault between the line and the ground.

EXAMPLE.—A ground occurred on a conductor of a cable 10,000 feet long composed of three No. 10 wires. One good wire was used to

complete the loop. On testing with one end of the battery grounded as in Fig. 53, the bridge was balanced with the following resistances: $m = 10$ ohms, $n = 1{,}000$ ohms, $p = 1{,}642$ ohms. Where was the ground, the resistance per 1,000 feet of the conductor being .9972 ohm?

SOLUTION.—The length of the loop formed by joining the two wires of the cable at the distant end will be 20,000 ft.; hence, $R = 20 \times .9972 = 19.944$, and $x = \frac{1{,}000 \times 19.944 - 10 \times 1{,}642}{1{,}000 + 10} = 3.4891$. Hence, the distance of the fault from the testing station must be

$$\frac{3.4891}{.9972} \times 1{,}000 = 3{,}498.9 \text{ ft. Ans.}$$

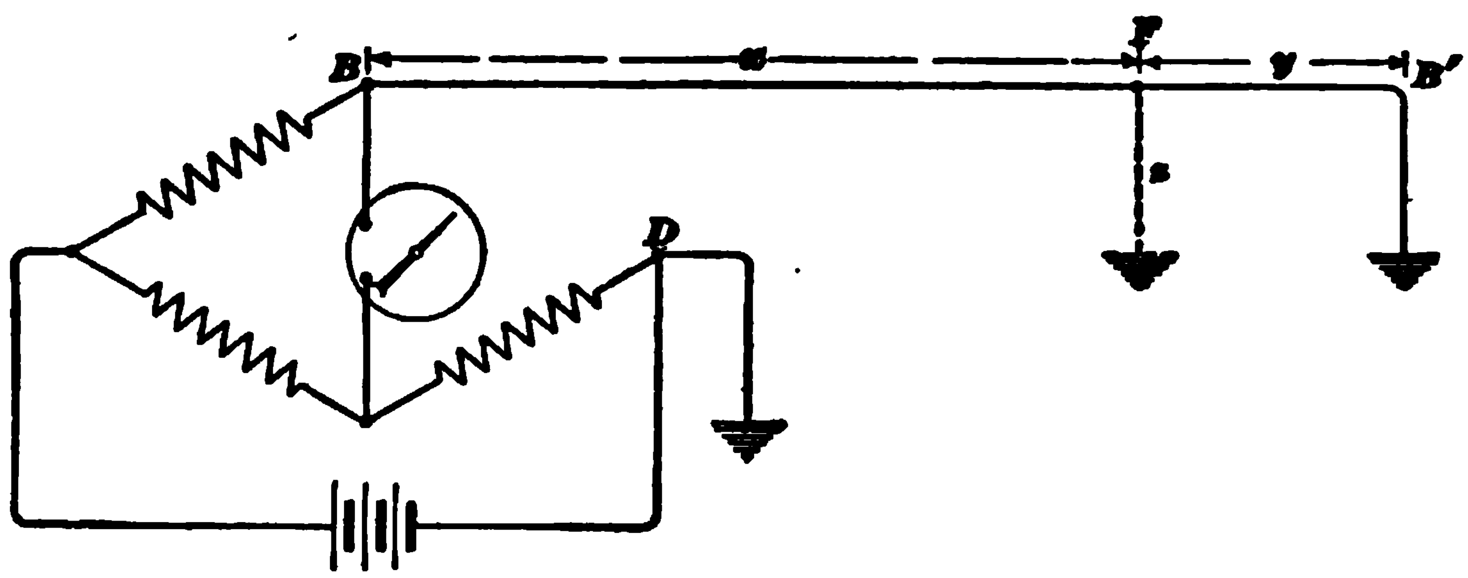


FIG. 54

58. Locating a Partial Ground Without an Available Good Wire.—The following method for locating a partial ground or leak is rather unreliable in practice, because the resistance of the partial ground may change

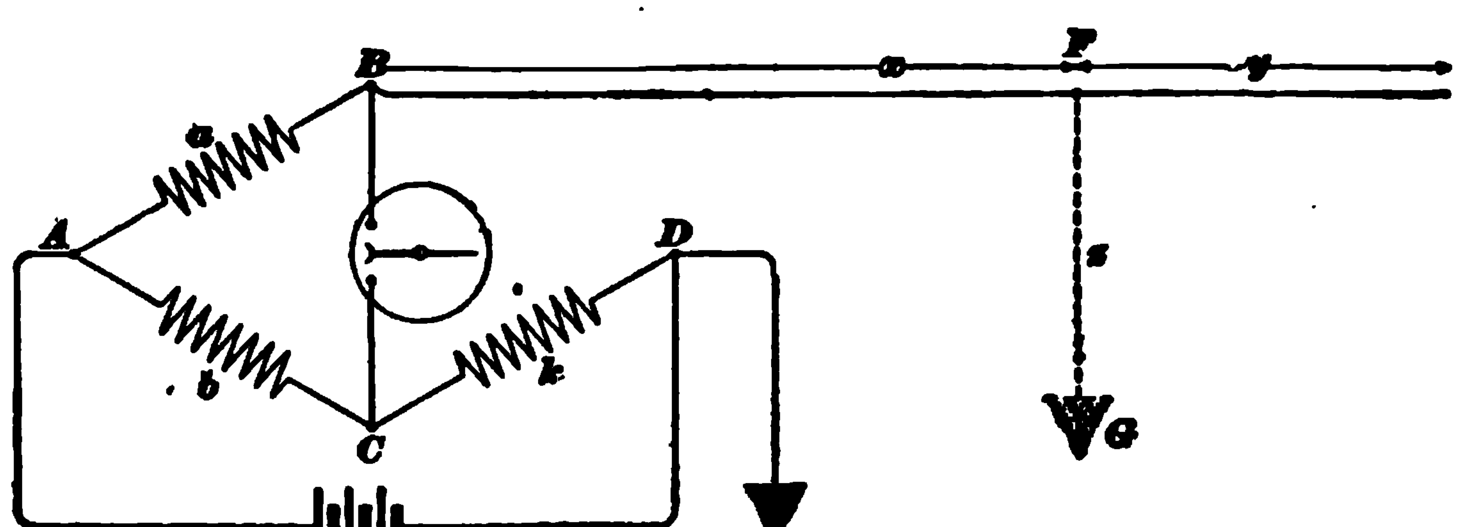


FIG. 55

between the two measurements, and so give a more or less incorrect result. However, it is about the only way where there is no available good wire and where the tests must be made from one end only. The normal resistance of the

line must be known from some previous measurement, unless it can be calculated from the length and size of the wire. Let this resistance be a; then measure the resistance of the line $B\,B'$, with the distant end B' grounded as shown in Fig. 54, and call this c. Also measure the resistance with the distant end open, as in Fig. 55, and call this b ohms. Then the resistance x to the partial ground from the testing station is given by the following formula:

$$x = c - \sqrt{(b-c)(a-c)} \qquad (5)$$

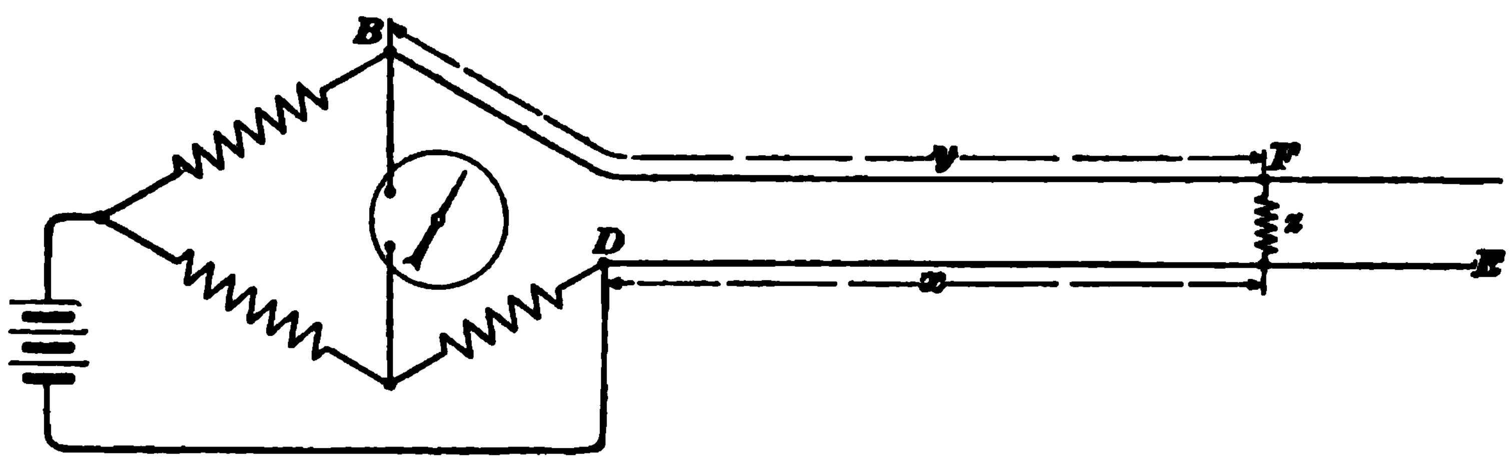


FIG. 56

By dividing x by the resistance per unit length of the wire, known from some previous measurements or by a calculation from its size, length, and a table of resistances for the kind of wire under consideration, the distance to the grounded point may be obtained.

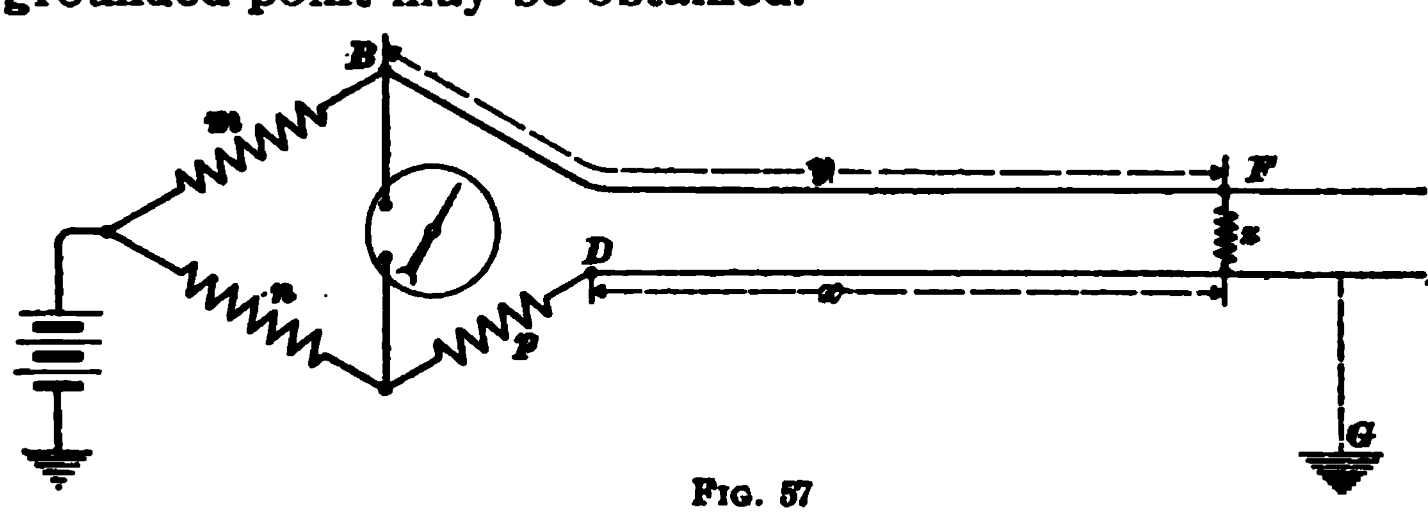


FIG. 57

59. To Locate a Cross by the Varley Loop Method. First insulate the distant ends of the two crossed wires. Then connect as shown in Fig. 56 and measure the resistance from D to B through the cross F. Let the resistance of the cross be z ohms and the resistance found by balancing the bridge be R ohms. Then,

$$R = x + y + z \qquad (1)$$

Now ground either wire, say DE, anywhere beyond the cross, and connect as shown in Fig. 57. When the bridge is again balanced, we have

$$\frac{m}{n} = \frac{y + z}{p + x} \qquad (2)$$

From equations (1) and (2), $x = \frac{nR - mp}{m + n}$.

This is the same as formula **4.** By dividing x by the resistance of the wire DE per unit length, we have the distance from D to the fault along the wire DE.

LOCATING GROUNDS AND CROSSES ON CONDUCTORS OF LOW RESISTANCE

60. The above tests, in which the location of a ground or cross is determined by means of resistance measurements, are capable of giving the location quite closely, provided the wire is fairly small, say less than No. 8 or 10 B. & S. When the wire is large, as it nearly always is in connection with power-transmission systems, bridge methods do not give the location close enough, because it is evident that a small resistance corresponds to a long length of conductor. The location of faults on these large conductors is of special importance in connection with underground distributing systems, and the bridge methods cannot usually be applied on account of the low resistance of the conductors. When a cross occurs between the conductors of an underground cable, it nearly always results in a ground also, because the consequent short circuit fuses the cable, thus making connection between the core and the sheath. One way of locating faults on underground cables is by the cut-and-try process already mentioned. A manhole is opened at a point near the middle of the line, and the cable is cut. Each half is then tested and the half on which the fault exists is then cut out at its middle point, and so on until the fault is located between two manholes. This method is slow and expensive, especially where high-tension cables are used, because the making of joints in such cables is a slow and costly operation.

61. Another method of locating faults is to run a heavy current through the cable so as to burn the insulation at the fault, and thus fill the duct and manhole with smoke. On opening the manholes the presence of the smoke indicates the location of the fault. This method, while more rapid and less expensive than the cut-and-try method, has the disadvantages that the burning of a cable, especially if near a manhole, is liable to injure other cables, and also that the burning is liable to ignite accumulated gases and thereby cause a subway explosion.

62. Fig. 58 shows, diagrammatically, a method recommended by Mr. Henry G. Stott,* which is particularly useful for locating faults on underground cables of large size. *A A*

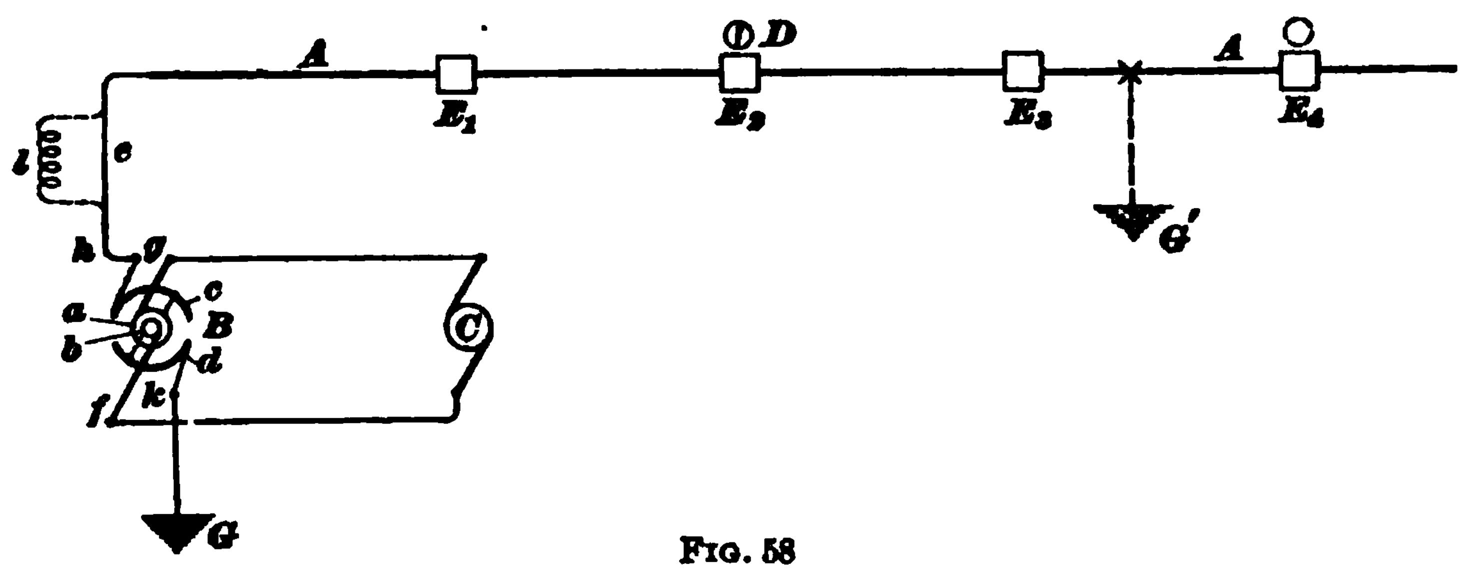


FIG. 58

is the cable running through a series of manholes E_1, E_2, etc. A ground has developed say at G', and this ground has to be located. C is a small direct-current dynamo; an arc light machine answers very well, because it maintains a fairly constant current, irrespective of the resistance of the circuit. B is a current reverser, which is revolved by means of a small motor. Brushes f, g, which press on the rings b, a, are connected to the terminals of C, and the contact arcs c, d are connected to the conductor and ground by means of brushes h, k. The rings a and b are connected to arcs c and d, so that as the contacts revolve, the current flowing through the cable to the fault G' and back to G is periodically reversed.

*Transactions American Institute of Electrical Engineers, Vol. XVIII.

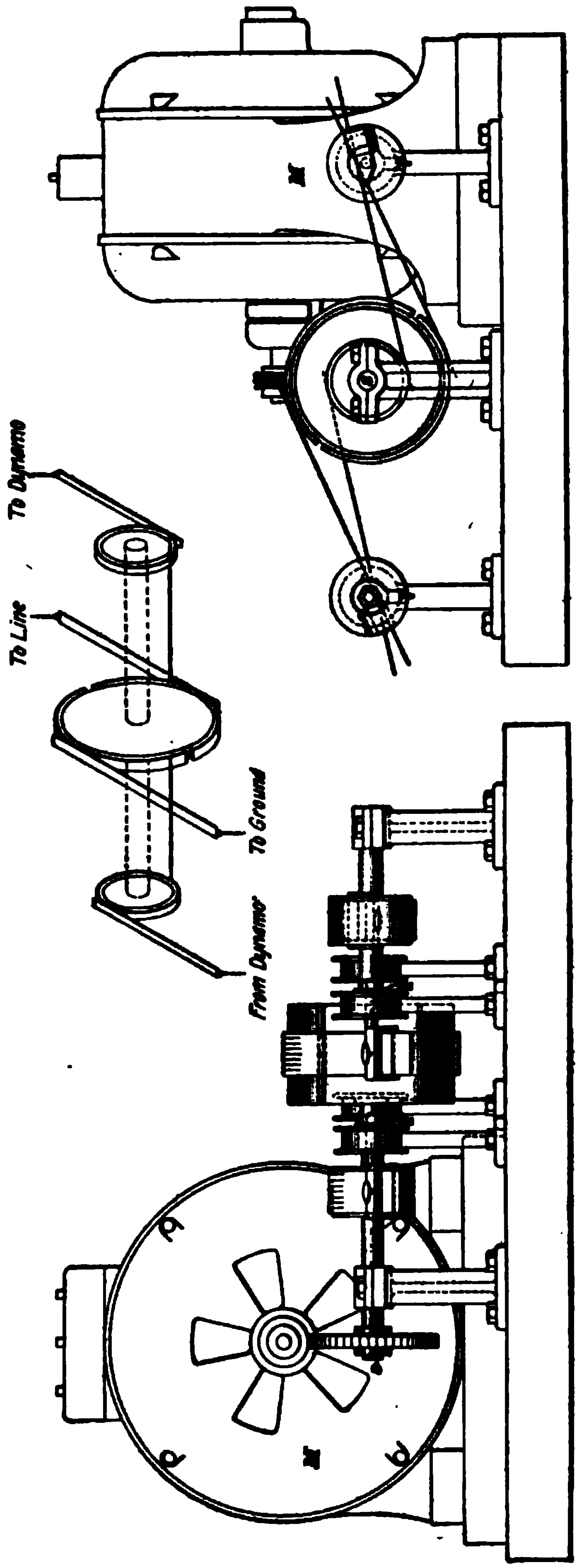


FIG. 59

The speed of the motor is such that the current is reversed once in about every 10 seconds. The fault is located by first opening a manhole about the middle of the line, say at E_3, and laying a compass D on the cable. The direct current, which need not be greater than 8 or 10 amperes, will cause the needle to swing first to one side and then to the other every 10 seconds. If the needle swings in this way at E_3, it shows that the fault is beyond E_3; hence, by this test, one-half of the cable is eliminated. The manhole is then closed and another test made at say E_4. At E_4 no reversals of the compass will be obtained, because the current does not flow in the cable beyond the fault. The fault is therefore located between E_3 and E_4; by opening a few intermediate manholes the

defective part is soon located between E_3 and E_4, and this section of cable can be removed and the fault remedied. It will be noticed that, with this method, the cable is not cut and the time required to make the test in each manhole is very short, so that the trouble is quickly located, and there are no joints to be made afterwards save those actually needed to replace the defective part of the cable.

In case the cable system carries alternating current and has no permanent ground attached to it, this device may be used for locating a fault even while the alternating current is on the system. The testing device is simply connected to the feeder network as shown, but in series between it and the network is placed a reactance coil, for example, the primary of a transformer, the circuit being opened at *e* and the coil connected in series as shown at *l*. This avoids damage to the dynamo *C* by preventing a rush of current from the alternating-current generators in case another ground should occur on the other side of the system while the test was being made, thus producing a short circuit. Before applying the test it is a good plan to break down the insulation resistance of the fault by applying a high potential, between the conductor and ground, for a few seconds.

Fig. 59 shows the style of reverser used in applying this test. An induction motor *M* drives the shaft *s* by means of a worm-gear. The two-part commutator revolves in oil so as to give a quick reversal of the current.

SWITCHBOARDS AND SWITCHBOARD APPLIANCES

SWITCHBOARD APPLIANCES

SWITCHES

1. Introduction.—The methods available for the transmission of electrical energy have been described in a general way, and it will now be necessary to examine more closely the various devices that are used for the control of the output of the generating plant. In order that a transmission system shall be under control, and also that the amount of the output, the condition of the lines, etc. shall be known, it is necessary to have various controlling and protective devices in the station. These are usually grouped together at one central point on the *switchboard*, and consist of switches, fuses, circuit-breakers, ammeters, voltmeters, ground detectors, lightning arresters, power factor indicators, wattmeters, and other auxiliary devices.

2. Probably the most important appliances on the switchboard are the **switches**, which are used for connecting or disconnecting circuits or dynamos from the rest of the system. Switches must be carefully selected with a view to the work that they have to perform. They must have ample carrying capacity and be capable of breaking the full-load current of the dynamo or circuit, without destructive burning or arcing. The style of switch used for any installation will depend on the voltage and current to be handled. For

convenience, we will consider switches as divided into two classes: *low-tension*, for handling pressures up to about 1,000 volts, and *high-tension*, for pressures above this amount.

LOW-TENSION SWITCHES

3. For pressures up to 1,000 volts, plain knife switches are generally used, though this style of switch with a broad separation of the blades and contacts has been used on pressures as high as 2,500 volts. For work of the latter class, however, it is preferable to use a switch of the quick-break variety, and even for pressures of 500 volts, quick-break knife switches are commonly used. Fig. 1 shows

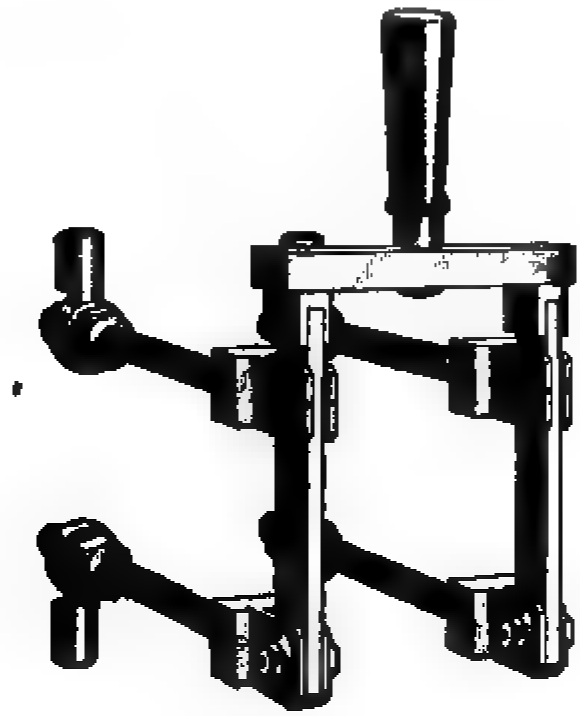


FIG. 1 FIG. 2

a typical two-pole knife switch designed for front connections and provided with fuses. Fig. 2 shows a similar switch without fuses and intended for mounting on a switchboard. When the switch is opened, connection is broken between the two clips at each side, thus opening both sides of the circuit. Knife switches should be substantially constructed and should have a contact surface at the clips of at least

1 square inch for every 50 to 100 amperes, the allowable current density being greater in small switches than in large ones. Bolted contacts will carry 200 amperes per square inch, and laminated contacts, such as are described later on in connection with circuit-breakers, will carry from 300 to

TABLE I

CURRENT DENSITIES FOR COPPER STUDS

Diameter of Stud Inches	Current Density Amperes per Square Inch	Diameter of Stud Inches	Current Density Amperes per Square Inch
$\frac{1}{2}$	1,200	$1\frac{1}{2}$	950
$\frac{3}{4}$	1,150	$1\frac{3}{4}$	850
1	1,100	2	800
$1\frac{1}{4}$	1,000	3	700

500 amperes per square inch. For copper studs the current densities, shown in Table I, should not be exceeded if the temperature rise is to be limited to about 20° C.

For the same temperature rise the current density must be smaller in large studs than in small ones, because in the large studs the heat is not so readily radiated.

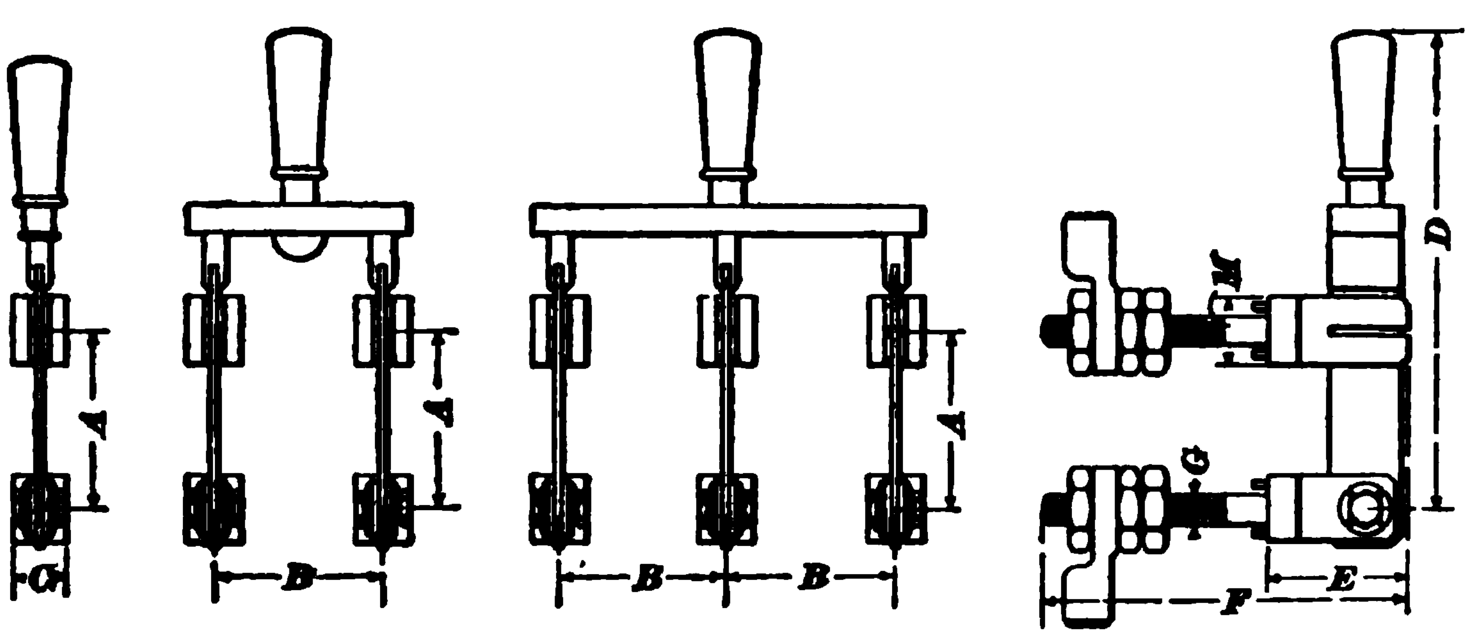


FIG. 3

4. The blades should be made of good conducting material, preferably of drawn copper, and the clips should be stiff enough to give a good, firm contact. For pure copper, the blades should have a cross-sectional area of about 1 square inch

per 1,000 amperes. Fig. 3, together with Table II, shows the dimensions, in inches, of General Electric knife switches.

Knife switches should always be mounted with the handles up; this is in accordance with a rule of the Fire Underwriters,

TABLE II

DIMENSIONS OF KNIFE SWITCHES

Capacity		Dimensions Common to All						Single-Pole		Double-Pole	Triple-Pole	Four Pole
Amp.	Volts	*A*	*B*	*E*	*F*	*G*	*M*	*C*	*D*	*D*	*D*	*D*
25	125	$1\frac{3}{8}$	$1\frac{5}{8}$	$1\frac{11}{16}$	$6\frac{3}{16}$	$\frac{3}{8}$	$\frac{5}{8}$	$\frac{5}{8}$	$4\frac{7}{16}$	$4\frac{5}{8}$	$4\frac{5}{8}$	$4\frac{3}{4}$
50	125	$1\frac{5}{8}$	$1\frac{7}{8}$	$1\frac{11}{16}$	$6\frac{3}{16}$	$\frac{3}{8}$	$\frac{5}{8}$	$\frac{5}{8}$	$4\frac{11}{16}$	$4\frac{7}{8}$	$4\frac{7}{8}$	5
100	125	2	$2\frac{1}{4}$	2	$6\frac{1}{2}$	$\frac{3}{8}$	$\frac{3}{4}$	$\frac{3}{4}$	$5\frac{3}{4}$	$6\frac{1}{2}$	$6\frac{1}{2}$	$6\frac{5}{8}$
25	250	$2\frac{1}{8}$	$2\frac{3}{8}$	$1\frac{11}{16}$	$6\frac{3}{16}$	$\frac{3}{8}$	$\frac{5}{8}$	$\frac{5}{8}$	$5\frac{3}{16}$	$5\frac{3}{8}$	$5\frac{3}{8}$	$5\frac{9}{16}$
50	250	$2\frac{5}{8}$	$2\frac{7}{8}$	$1\frac{11}{16}$	$6\frac{3}{16}$	$\frac{3}{8}$	$\frac{5}{8}$	$\frac{5}{8}$	$5\frac{11}{16}$	$5\frac{7}{8}$	$5\frac{7}{8}$	$6\frac{1}{16}$
100	250	$2\frac{3}{4}$	3	2	$6\frac{1}{2}$	$\frac{3}{8}$	$\frac{3}{4}$	$\frac{3}{4}$	$6\frac{1}{2}$	$7\frac{1}{4}$	$7\frac{1}{4}$	$7\frac{7}{16}$
200	125–250	$3\frac{1}{4}$	$3\frac{3}{8}$	$2\frac{7}{16}$	$6\frac{15}{16}$	$\frac{1}{2}$	1	$\frac{7}{8}$	$7\frac{3}{4}$	$8\frac{1}{8}$	$8\frac{1}{8}$	$8\frac{1}{4}$
300	125–250	$3\frac{5}{8}$	$3\frac{1}{2}$	$3\frac{1}{4}$	$7\frac{3}{4}$	$\frac{5}{8}$	$1\frac{3}{8}$	1	9	$9\frac{1}{2}$	$9\frac{1}{2}$	$9\frac{5}{8}$
500	125–250	$4\frac{3}{4}$	$4\frac{1}{8}$	$4\frac{1}{4}$	$8\frac{3}{4}$	$\frac{3}{4}$	$2\frac{1}{4}$	$1\frac{3}{8}$	$11\frac{1}{4}$	$11\frac{7}{8}$	$11\frac{7}{8}$	$13\frac{1}{8}$
800	125–250	$5\frac{1}{2}$	5	5	$9\frac{1}{2}$	1	$2\frac{3}{4}$	2	$12\frac{3}{4}$	$13\frac{3}{8}$	$13\frac{3}{8}$	$14\frac{1}{8}$
1,200	125–250	$5\frac{1}{2}$	$5\frac{3}{4}$	$4\frac{1}{2}$	10	$1\frac{1}{4}$	$2\frac{1}{2}$	$1\frac{3}{4}$	$12\frac{5}{8}$	$13\frac{1}{4}$	$13\frac{1}{4}$	
1,500	125–250	$5\frac{3}{4}$	6	$4\frac{7}{8}$	$10\frac{3}{8}$	$1\frac{1}{2}$	$2\frac{3}{4}$	$2\frac{3}{4}$	13	$13\frac{5}{8}$	$13\frac{5}{8}$	

which requires switches to be so placed that when open they will not tend to fall closed of their own accord.

5. Fig. 4 shows a style of quick-break switch that has proved very successful and is suitable for pressures as high as 2,000 to 2,500 volts if the current is not large. It has been very widely used on direct-current railway switchboards. The switch blade, of drawn copper, is made in halves

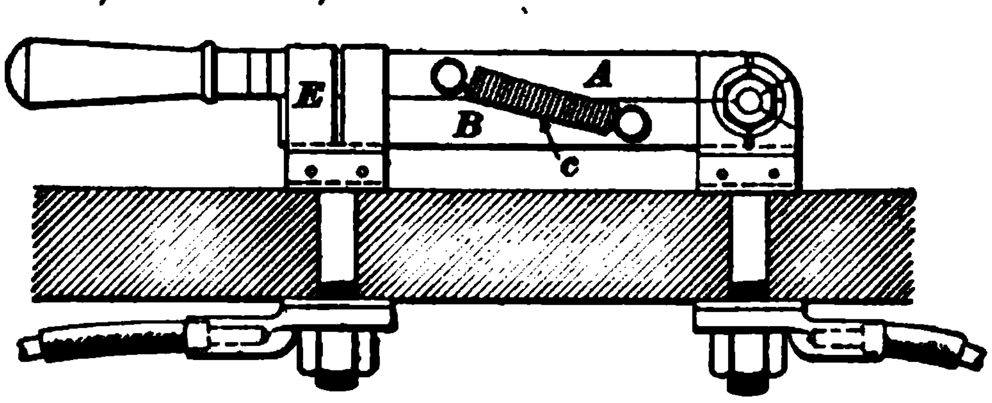


Fig. 4

A, *B*, which are connected by two springs *c*, one on each side of the blade. When the handle is pulled out, the half *A* leaves the clip *E* and thus stretches the springs. When the bottom blade flies out, it leaves clip *E* very quickly, thus drawing out the arc and breaking it almost instantaneously.

HIGH-TENSION SWITCHES

6. In long-distance transmission plants using alternating current, the pressures are very high, and in some cases also the volume of current is large. A switch to interrupt a heavy current at high pressure has to be carefully designed, and a great many types have been brought out. These may be divided into three general classes:* (1) Those in which the arc is interrupted in the open air; (2) those in which the arc is interrupted in a confined space; (3) those in which the arc is broken under oil.

These switches may be arranged for hand operation or they may be designed to operate automatically in case the current exceeds the allowable limit. If used in the latter way, they are generally called *circuit-breakers* to distinguish them from the non-automatic type. In many cases it is necessary to have high-tension switches arranged so that they may be operated from a distant point, because it is not practicable or even desirable to have high-pressure switches of large capacity mounted on or near the operating board.

SWITCHES BREAKING ARC IN OPEN AIR

7. In this type of switch the arc is simply pulled out until it is broken. Fig. 5 shows a modification of the switch shown in Fig. 4. This switch will handle a moderate current at pressures up to 5,000 or 6,000 volts, but where the volume of current is large, it is better to use a switch belonging to class (3).

The switch (Fig. 5) is constructed so as to give a long, quick break, and is mounted on grooved insulators *1*, *2*, *3*, *4*. This insulating material passes through the panel, so that in no place does the metal switch stud come in contact with the marble. This is a necessary precaution in cases where very high pressures are handled, because the marble cannot be depended on to give good enough insulation. Blade *A* has

*Classification given by E. W. Rice, Jr. Transactions American Institute Electrical Engineers, Vol. XVIII.

a hole in the end instead of a handle, and the switch is pulled open by means of a hook in the end of a handle about 3 feet long, thus allowing the attendant to stand back some distance and avoid the danger of being burned by the arc. To avoid arcing from one switch to the next, marble barriers *C* are mounted at right angles to the main part of the board.

For handling very high pressures, such as 20,000 volts and upwards, air-break switches have been used to quite a large extent. In these switches, the movable contact is generally mounted on one end of a long arm, so that when the arm is thrown out, a break of several feet is made in the circuit.

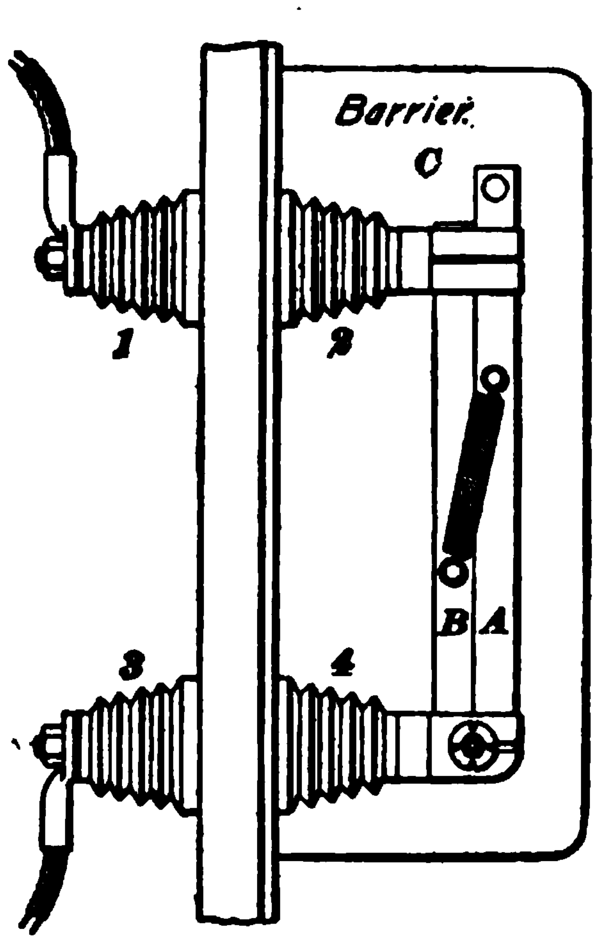


FIG. 5

8. Stanley Plug Switch. Fig. 6 shows a type of air-break switch made by the Stanley Electric Manufacturing Company, and used on pressures as high as 30,000 volts, at which pressure it is capable of handling a current of 25 amperes. A long wooden handle *a* is provided with a terminal *b* on its upper end, and this terminal is connected to a plug *c* by means of a flexible cable *d*. When plug *c* is inserted, it makes contact with a terminal sunk well below the surface of the marble, where it cannot be touched accidentally. Also, it is locked in position, so that the circuit cannot be accidentally opened at this point. The terminals *e* and *f* are mounted on ribbed porcelain insulators, and are made in the form of tapered points, as shown, so that the tip *b* may be slid over them. Hard-rubber guides arranged below the porcelain insulators engage with the projection cast on *b*, so that the handle *a* must be pulled straight down for a short distance when the switch is being opened, thus preventing terminals *e*, *f* from being bent.

When the handle has been pushed up into place, it is held by clamps *g*, *h*. The switch shown in Fig. 6 is of the double-throw type, i. e., terminal *c* can be connected to either *e* or *f*; a marble barrier *k* is placed between the terminals to prevent arcing across. When the switch is opened, the handle is pulled down until the contact is separated from the taper plug, and it is then swung back over the operator's shoulder and moved away from the board until the arc is ruptured. The tapered terminals and the terminal on the handle are provided with zinc tips, as it has been found that the arcing does not roughen up the zinc to the same extent as copper. One advantage of this type of switch is that the live terminals are at the top of the board out of reach of the operator. By unlocking plug *c*, the handle with its cable may be removed entirely if it is desired to clear the board.

FIG. 6

SWITCHES BREAKING THE ARC IN A CONFINED SPACE

9. Westinghouse Plunger Switch.—Fig. 7 shows a Westinghouse switch where the arc is broken in a confined space. The terminals are mounted at each end of a porcelain cylinder. A copper rod or plunger passing through these contacts or bushings completes the circuit, and when the plunger is withdrawn, the arc is formed in the confined space between the bushings. A small outlet is provided in the side of the tube, and when the arc is formed, the blast caused by the sudden expansion of the air in the confined space, together with the cooling action of the porcelain walls,

extinguishes the arc. If the pressure to be handled is very high, a number of these cylinders are connected in series, thus producing a long break. The cylinders *1*, *2*, *3*, etc. and plungers *1'*, *2'*, *3'* are mounted on the back of the board and are operated by a lever on the front. In the figure the switch is shown thrown out, but when the plunger is in, bushings *a* and *b*, *c* and *d* are connected together, and the path of the current is *a-b-c-d-c* to line. When the plunger is withdrawn, the arc is broken between *a* and *b*, *c* and *d*.

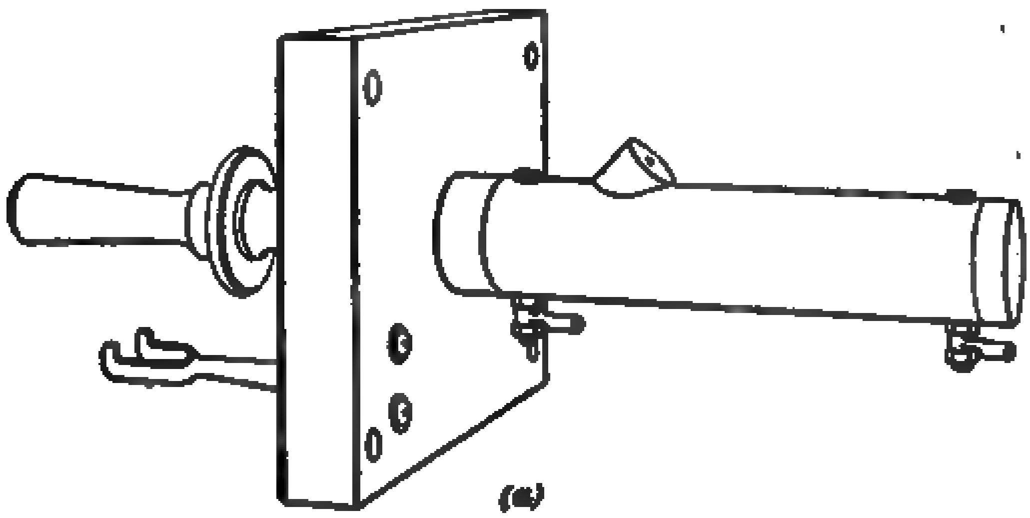
FIG. 7

10. Stanley Slide Switch and Circuit-Breaker.

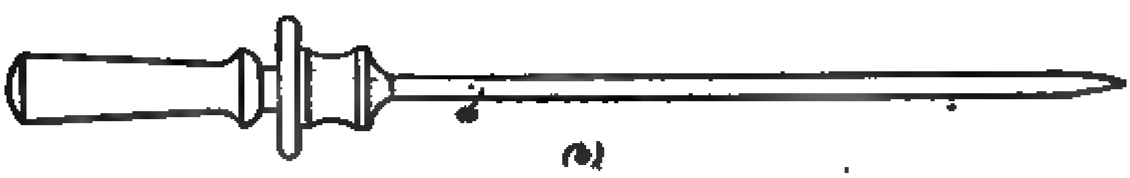
FIG. 8

Fig. 8 shows a Stanley slide switch provided with an

automatic attachment that will open the switch whenever the current exceeds the amount for which the circuit-breaking device is adjusted. The attachment consists of a solenoid *a* through which the main current flows. When the current exceeds the allowable amount, the solenoid releases a catch and a spring throws the switch out. If it is not desired to use the switch as a circuit-breaker, the automatic device can be cut out. The switch terminals are mounted in the insu-



(a)



(b)

FIG. 9

lating blocks *b*, *b'*, of which there are two for each pole; in this case there are six terminals, the switch being three-pole. For each pole there is a cross-piece *c* provided with blades *d*, *d'* that make contact with the terminals when they are forced in by swinging the handle *d* up. The motion of *d* is transmitted to the cross-pieces *c* by means of a rack and pinion, and when the switch is opened the blades are withdrawn from the

clips; as soon as they leave the insulating pieces, a shutter arrangement closes the opening, thus preventing the arc from following the blades. Switches of this type are made in a number of different sizes and are capable of handling as high as 60 amperes at 3,300 volts. The present practice, however, is to use oil switches for most high-pressure work.

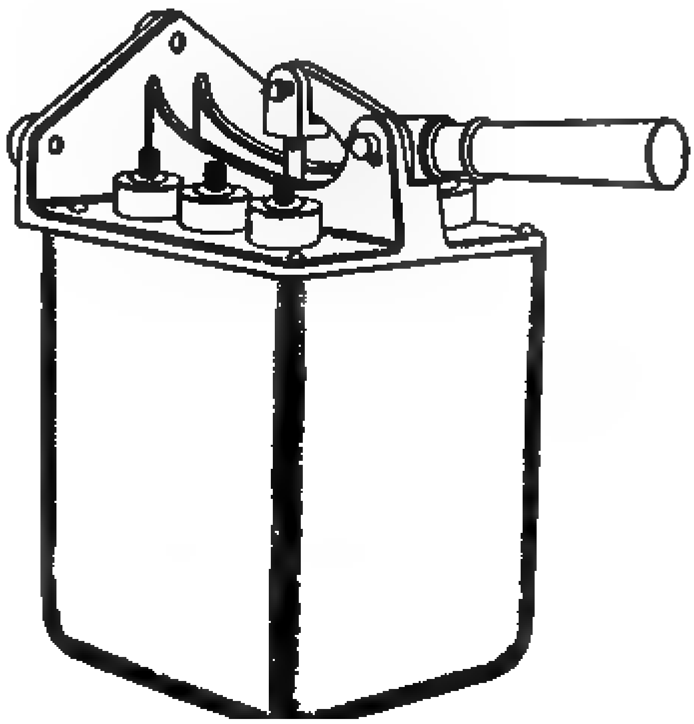
11. Stanley Stab Switch.—Fig. 9 shows a simple form of high-tension switch that is capable of handling a current of 10 amperes at pressures as high as 7,000 volts. When the rod *a* is inserted, contact is made between the bushings *b*, *c* mounted in a thick fiber insulating tube. When *a* is withdrawn, the marble ball *d* drops from the cavity *e* in which it is held by the rod, and takes the position shown, thus effectually smothering the arc. The vent *f* provides an exit for the heated air. Switches of this type are particularly adapted for high-pressure, series-arc lighting circuits or series-incandescent lighting circuits.

SWITCHES BREAKING ARC UNDER OIL

12. It has been found that circuits carrying large currents at high pressure can be successfully broken by separating the terminals under oil, and oil-break switches have come much into use within the last few years. Circuits in which there is more or less inductance, producing a lagging current, require more effective switching devices than those in which there is no inductance, because the induced E. M. F. always tends to prolong the arcing when the switch is opened. Oil switches have proved very efficient on circuits of this kind. As soon as the switch terminals are separated under oil, the oil fills the gap and arcing is effectually suppressed with a comparatively short separation of the terminals. It was at first thought that the very sudden break caused by a switch of this kind might give rise to severe strains on the insulation of the system, but this has not proved to be the case, and oil switches are now very largely used, both in central stations and also in connection with motors or other apparatus using alternating current. There are many different

reliable makes of oil switches, but for purposes of illustration we will select a few examples of the General Electric type.

13. General Electric Oil Switches.—Fig. 10 (*a*) and (*b*) shows a switch designed for mounting on the front of the switchboard or for individual use with motors or other apparatus. The same style of switch is made for mounting behind the switchboard with the operating handle on the front of the board; (*b*) shows the switch with the oil tank removed. In this case a triple-pole, single-throw switch is illustrated, though the same type is made in single-pole, double-pole, and four-pole, and for either single-throw or double-throw. The terminals *a*, *a*, *a* are mounted in the porcelain insulators *b*, *b*, *b*. The contacts *c* are hinged as shown, and are connected together by a wooden cross-piece *e* connected to the operating handle. The other contacts *d* make a firm wiping contact with *c* when the switch is closed. The wires leading to and from the switch are attached to the terminals *a*, *a*, *a*



(*a*)
FIG. 10

so that they do not pass through the oil tank, and there is, therefore, no chance for oil leakage if the tank is not filled too full. This type of switch is recommended for use with all inductive appliances, such as induction motors, that operate at 250 volts or higher. It is not intended for circuits operating at pressures higher than 3,500 volts or in cases where the load exceeds 850 to 1,200 kilowatts, three-phase, under emergency conditions; i. e., under a short circuit or very heavy overload.

14. Fig. 11 (*a*), (*b*), and (*c*) shows another General Electric switch of larger capacity. This is made single-, double-, triple-, and four-pole, and for single-throw only. The load that it can rupture under emergency conditions must not exceed 3,500 kilowatts, and the pressure 6,600 volts. For potentials exceeding 5,000 volts, the switch is not mounted on the back of the switchboard, as shown in Fig. 11, but is placed in a fireproof compartment entirely detached from the board. The operating handle on the board is connected with the switch by means of a series of levers. By this arrangement, the danger of fire at the switchboard is minimized and the operating devices can be entirely separated from the high-tension parts of the switch. Fig. 12 shows the general arrangement referred to, though, of course, the actual arrangement of the levers would depend on the relative location of the operating board and switch. These switches are arranged for simple hand control, or they can be provided with an attachment that will open them automatically in case the load becomes excessive, thus combining the feature of a switch with that of an automatic circuit-breaker. Fig. 11 (*a*) shows the operating handle provided with the automatic attachment; (*b*) shows the arrangement for hand control; (*c*) shows the construction of the switch proper with the oil tank removed. The terminals are held in the porcelain insulators *b*, *b*, *b*, which are ribbed in order to interpose a large leakage surface between the terminals and the framework of the switch. When the operating handle is pushed in, the metal cross-pieces *c*, *c*, *c* are raised by the

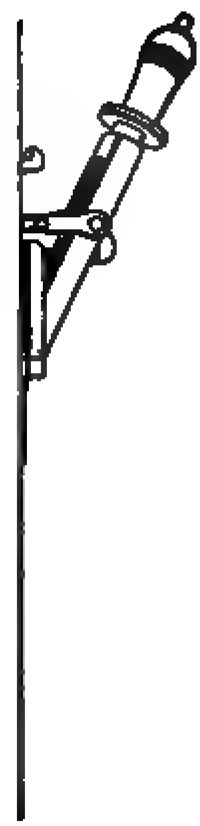


FIG. 11

system of levers and brought into contact with the fingers *d*, *d*, *d*, thus completing the circuit. Each cross-piece *c* is attached to a wooden rod *e*, and these rods are attached to a common crosshead that is moved up or down by the levers controlled by the operating handle. When the oil tank is in place, the contacts *c* and *d* are completely submerged in oil.

FIG. 12

15. The automatic tripping mechanism used when the switch is mounted on the board is shown in (*a*). It consists of two solenoids *f*, *f*, which, when the current becomes excessive, draw up their cores, which strike the lever *g*, *g*. This releases the link *h* that connects the operating handle with the switch and allows the switch terminals to separate. The link *h* slides out through the operating handle, but the handle itself remains in. The projecting link, therefore, acts as an indicator and shows that the switch has opened automatically. When the switch is opened by hand, the button *k* on top of the operating handle must first be pressed down.

16. Fig. 13 shows the connections for the tripping coils when the tripping mechanism is placed at the switch as in Fig. 11. The windings of the coils, Fig. 13, are connected to the secondaries of two current transformers, the primaries of which are in series with the mains, as shown. If the current in the mains becomes excessive, the current in the secondaries and tripping coils increases in like proportion, and if the current exceeds the value for which the armatures

of the coils are adjusted, the switch is opened by the operation of either one or both of the coils.

When the switch is not mounted on the board, the tripping coil is operated through an overload relay or auxiliary pair of magnets, as shown in Fig. 14. In Fig. 12, the tripping coil is located at *a*, and consists of a single coil, the armature of which moves the light wooden rod *b* and allows the switch to open promptly whenever there is an overload. In Fig. 14, *a* is the tripping coil and *b*, *c* the coils of the overload relay situated on the switchboard or at any other convenient point. Under normal conditions the contacts *d*, *e* of

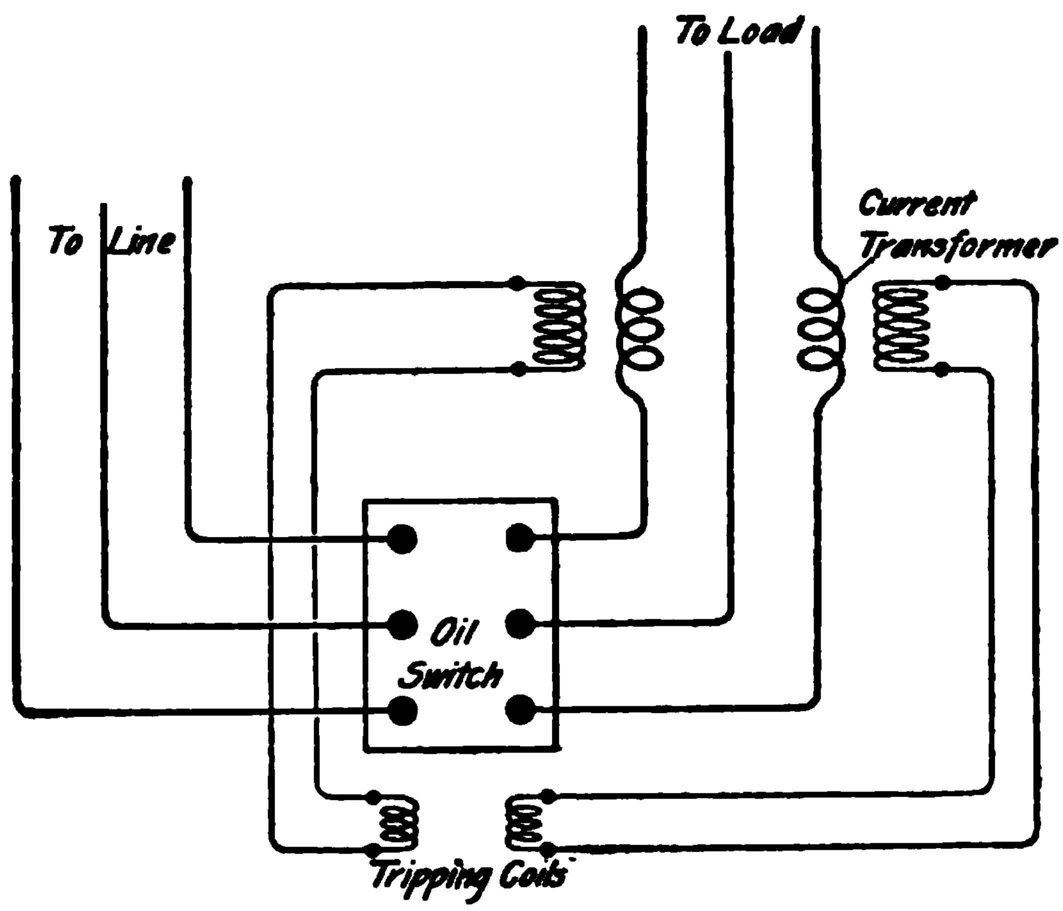


FIG. 13

the relay short-circuit the tripping coil, but in case the current becomes excessive, either one or both of the coils draw up their cores and raise contacts *d*, *e*, thus making the current from the series-transformers take the path through the tripping coil *a* and opening the switch.

17. Oil Switch of Large Capacity.—Fig. 15 shows two views of a General Electric oil switch of large capacity for use in central stations handling large alternating currents at high pressure. The switch is arranged for control from a distant point, the movements being effected by means of an

electric motor. These switches have also been built for operation by compressed air, and the Westinghouse Company make a somewhat similar switch operated by solenoids. The casing of the switch shown in Fig. 15 is made of brick, and is provided with a removable iron door. The casing is divided into three compartments, one for each phase, and since they are separated by brick partitions, a burn-out, if it should occur, cannot spread to other parts. These switches are designed with a view to using the smallest possible amount of oil, because where there are a large number placed in a plant, the presence of a large quantity of oil in the switches would introduce a serious

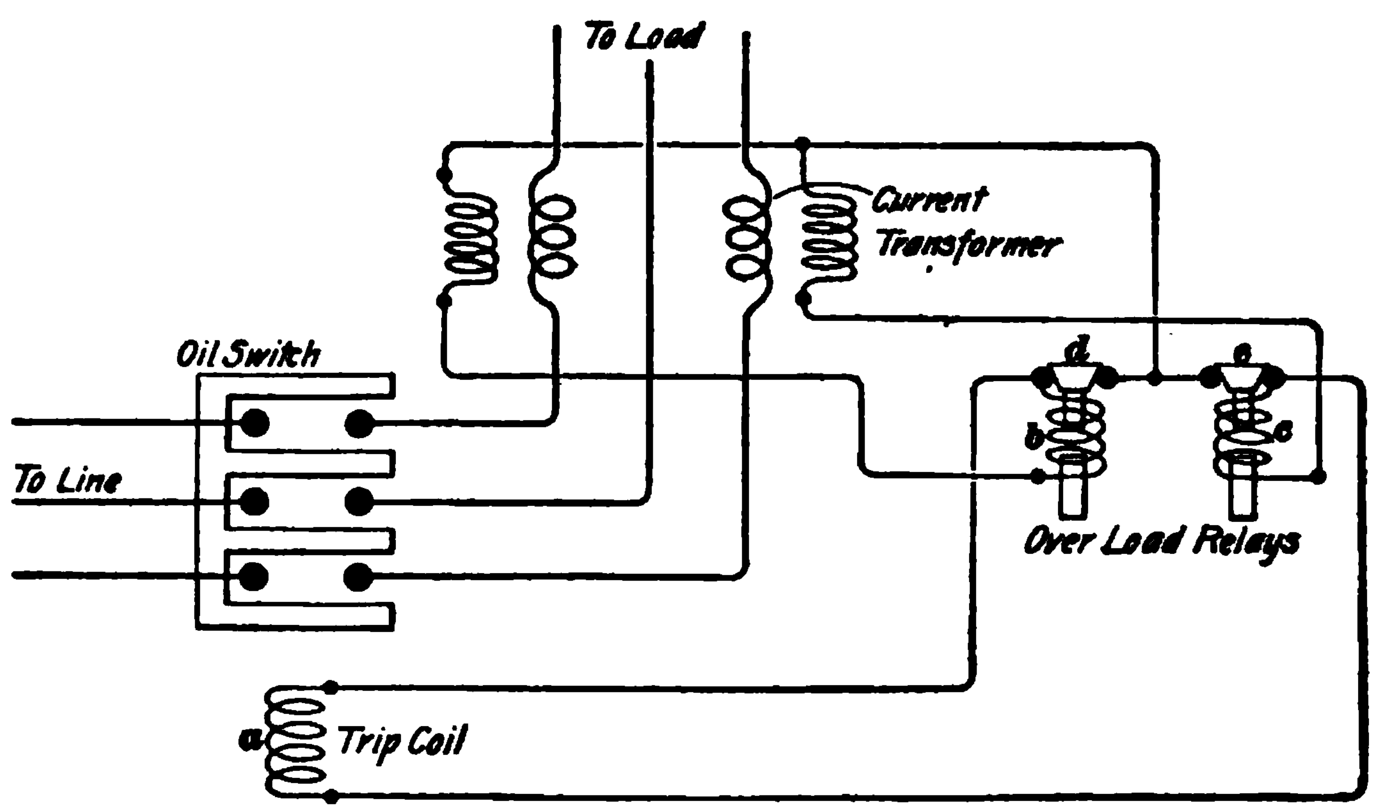
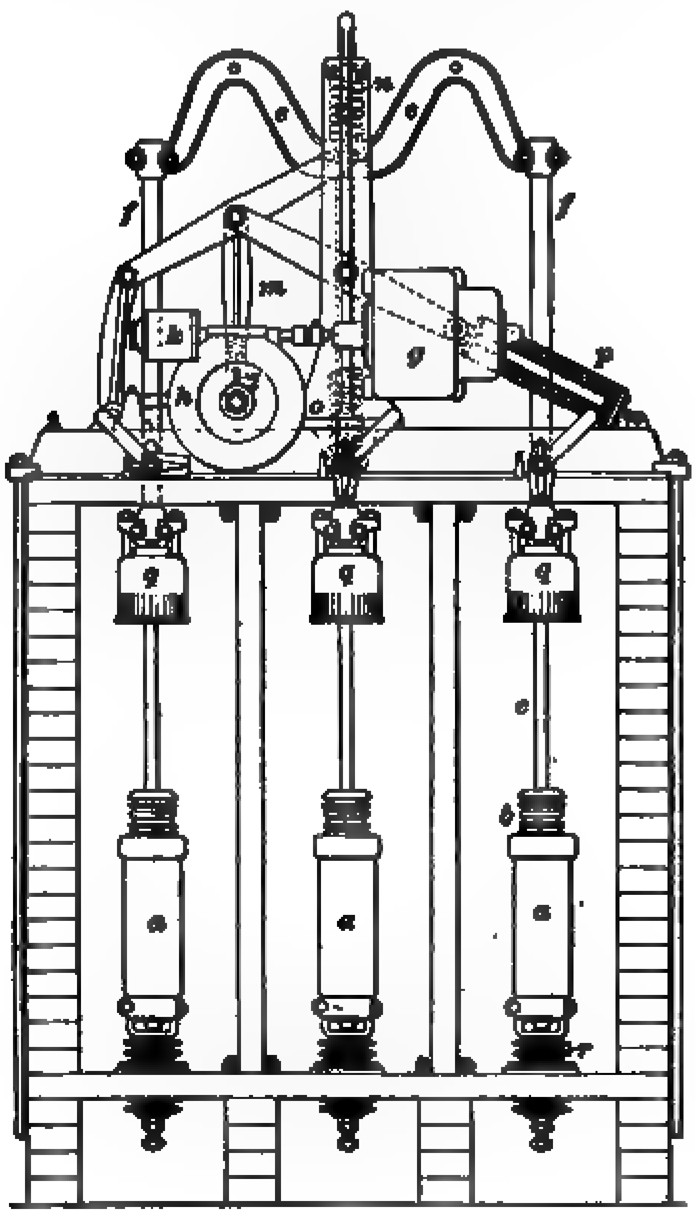


FIG. 14.

fire risk. In each compartment is a pair of brass cylinders *a*, *a* with a contact sleeve at the bottom of each. These cans or cylinders are lined with insulating material, are filled with oil, and are provided with porcelain insulating sleeves *b* at the top through which slide copper rods *c*. The two rods are connected together by the cross-piece *d*, so that when the rods are pushed down into the contact sleeves in the bottom of the cylinders, the two cylinders are electrically connected, the current passing from one cylinder to the other by way of rods *c*, *c* and cross-piece *d*. The cross-pieces *d* are attached to a crosshead *e* by means of wooden rods *f*, and the motion of the crosshead is controlled by means of the motor *g*.

The motor is thrown into gear with a worm that operates a worm-wheel in the casing *h*, whenever the solenoid *k* is excited from the switchboard. On the worm-gear shaft is a crank *l* which together with a link *m* forms a togglejoint. When the switch is out, as shown in the figure, spring *n* is compressed and the switch tends to close, but is prevented



(a) (b)

FIG. 15

from doing so because the toggle *l m* is on center. As soon as the motor is started from the switchboard, the crank *l* is moved off center and the crosshead *e* is at once forced down. The crank *l* is driven from the worm-gear by means of a ratchet, so that as soon as the toggle is moved off center,

the crank is carried around through nearly a half revolution independently of the movement of the motor. As soon as the crank stops, the ratchet at once takes hold and the crank is turned through the remainder of the half revolution until the toggle is again on center. The switch is now completely closed, and the motor is stopped automatically by means of a rotating switch moved by the worm-gear shaft. When the switch is closed, spring o is compressed and springs p are stretched. The switch is opened by starting the motor from the switchboard, as before, thus throwing the toggle off center again and allowing the springs to throw up the cross-head. In the opening operation, the springs p assist spring o, so that the opening is quicker than the closing, the time

FIG. 16

required being about 1 second. For switches that have to handle large currents, the rods c, c are provided with auxiliary bell-shaped contacts q, q, which, when moved down to the dotted position, make contact with the upper part of the cylinders, thus relieving the rods of the current. When the switch moves up, these contacts leave the cylinder before the contact is broken inside the cylinder, so that no arcing takes place at the auxiliary contacts. The cylinders are mounted on ribbed porcelain insulators r, r, and are arranged so that they can be easily removed from these supports. The switch shown in Fig. 15 has a range of movement of 17 inches and is capable of handling 300 to 800 amperes at 12,000 volts.

18. Stanley Oil Switches.—Figs. 16 and 17 show two types of **Stanley oil switch.** The switch shown in Fig. 16 is of the double-pole, double-throw type with the oil tanks mounted side by side. Fig. 17 shows a three-pole, single-throw switch with the tanks mounted one behind the other, so that the switch can be mounted on a narrow panel. The oil tanks *a*, *b*, *c* are of cast iron with an enamel lining, and are mounted under the marble slab *d* to which the fixed switch terminals *e* are attached. The slab *d* is supported by iron castings, and the switch arms *f* are operated by means of the levers, as indicated, thus throwing the blades *g* into or out of contact with the fixed clips. The terminals *t* are protected by wooden boxes, and the operating handle *k* is thoroughly

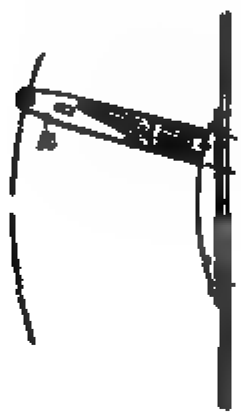


FIG. 17

insulated from the working parts of the switch by the wooden arm *l*. The tanks are arranged so that they can be easily refilled. There are two breaks in each leg of the circuit; in Fig. 17, for example, there are two fixed clips *e* in each tank, and the two corresponding blades *g* are connected together.

BUS-BARS

19. Bus-bars should have a cross-section of at least 1 square inch per 1,000 amperes and should be arranged so that the heat generated in them can be readily radiated. They should be substantially mounted and carefully insulated, particularly in cases where a high pressure is used. The bars are usually of flat rectangular cross-section; and if

large current-carrying capacity is required, a number of thin bars are built up with air spaces between to allow ventilation. Thus, a bar made up of four bars $\frac{1}{4}$ inch thick with a $\frac{1}{4}$-inch air space between each bar would be much better than a solid bar 1 inch thick. Heavy solid bars should not on any account be used with alternating current. Where bars are made up of a number of thin bars with air spaces between, joints are readily made by interleaving the bars and bolting through, thus giving a large contact area. Round bars and copper tubes are occasionally used for bus-bars but they are not as desirable as flat bars except,

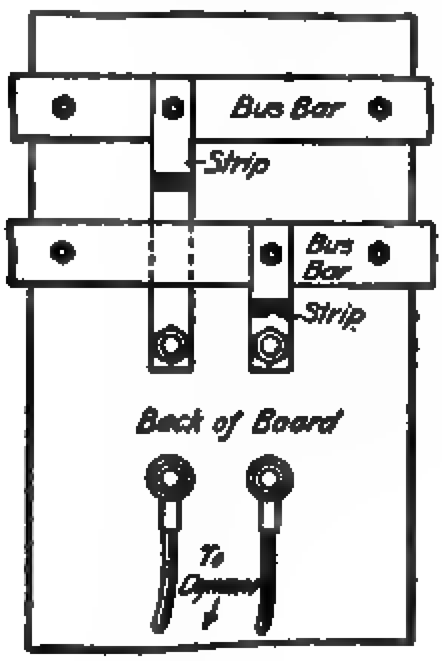


FIG. 18

perhaps, for high-tension boards, where the current to be handled is small and where it is desirable to have the bars covered with insulating material.

Fig. 18 shows a simple method of mounting bus-bars for small low-pressure switchboards. Fig. 19 shows a method that has been largely used on 500-volt railway switchboards.

20. Carrying Capacity of Bus-Bars.—Bus-bars should be of liberal cross-section, otherwise the loss in them may be considerable. For aluminum bars, a density of from 500 to 600 amperes per square inch is allowable. Cast copper is much inferior to rolled or drawn copper as a conductor,

and the density in cast bars, studs, or fittings should not exceed 500 amperes per square inch. Brass can carry from 100 to 350 amperes per square inch, depending on the amount of copper in its make-up.

21. Mounting for High-Tension Bus-Bars.—When bus-bars have to handle a large current at high pressure, it is very important that they be mounted so that there is practically no possibility of a short circuit taking place between them. A short circuit on such bars might cause a great deal of damage, particularly if a number of machines happened to be feeding into the bars at the time. It has

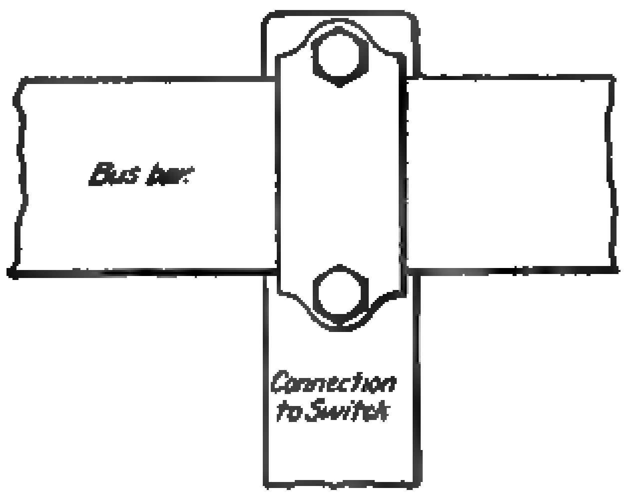


FIG. 19

become customary, therefore, in large stations supplying current at high pressure, to mount the bars on fireproof supports and separate them by fireproof partitions so that each bar shall be in a compartment by itself. Fig. 20 shows the method of mounting 6,600-volt bus-bars in a large station in New York city. The bus-bar *a* is made up of four rolled copper bars 3 inches wide by $\frac{1}{8}$ inch thick, and is bolted to a stud *b* that is covered with an insulating tube *c*. The bar, with its connecting stud, is supported on a firebrick slab *d*, this slab being built into the brickwork *e f*. Thorough insulation is provided by the grooved porcelain insulators *g*, *g*,

and connections are made to the bar by means of the cable terminals *h*, *h* and plate *k*. Firebrick or soapstone slabs

FIG. 20

projecting at right angles to the wall *e f* are used as barriers between adjacent bars.

VOLTMETER CONNECTIONS

22. It is customary, on switchboards, to make one voltmeter answer for several machines or circuits by providing

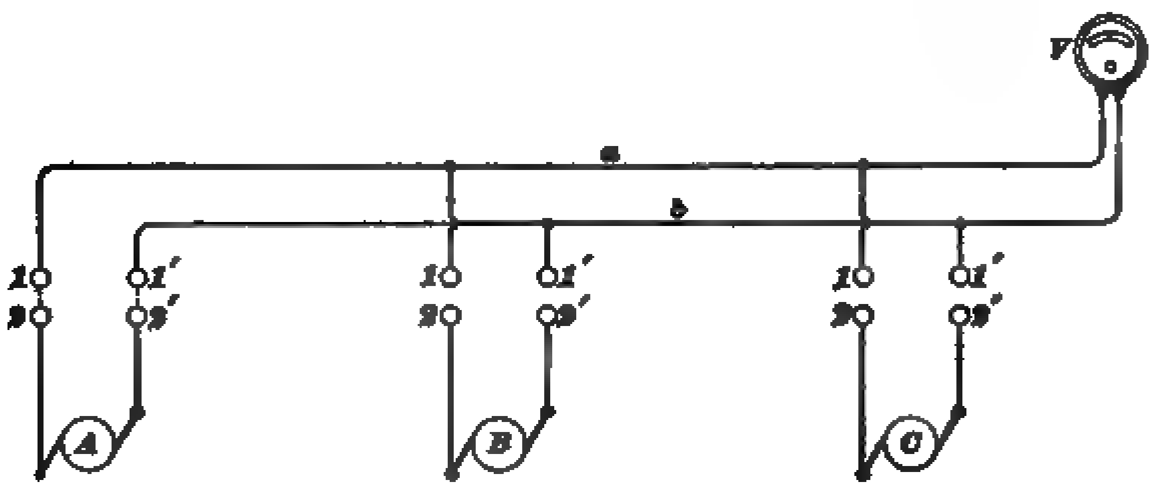


FIG. 21

suitable voltmeter plugs or a voltmeter switch by means of which the instrument can be connected to the circuit or

machine on which a voltage reading is desired. Figs. 21 and 22 show a common plugging arrangement. A pair of voltmeter bus-wires *a*, *b* are connected to the voltmeter *V*, Fig. 21, and taps connect from *a*, *b* to the plug receptacles *1*, *1′*. The different dynamos are connected to *2*, *2′* and when a voltmeter reading is desired on, say, machine *A*, a plug, Fig. 22, is inserted into the receptacle, thus connecting *1*, *2* and *1′*, *2′*.

FIG. 22

23. Pressure Wires.—In many cases, particularly on systems supplying current for lighting purposes, it is necessary to know the pressure at the point where the current is utilized rather than at the station. In some cases, especially on low-pressure, three-wire systems, *pressure wires* *a*, *b* are run back to the station, as shown in Fig. 23.

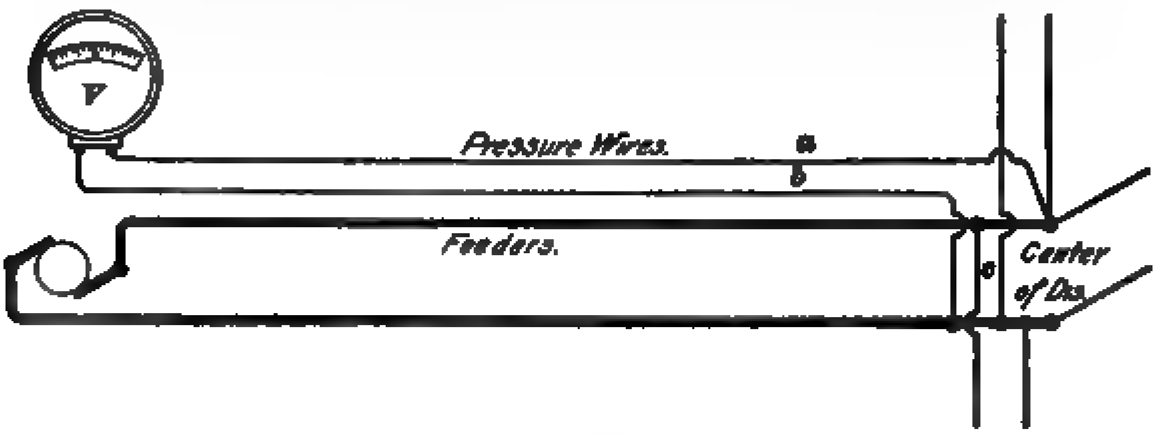


FIG. 23

The current required to operate the voltmeter is so small that there is practically no drop in the pressure wires; they can, therefore, be of small cross-section (usually No. 8 or No. 10 when strung on poles); insulated iron wire is sometimes used for the purpose.

24. Compensating Voltmeter.—In order to avoid the use of pressure wires, *compensating voltmeters*, or *compensators*, are sometimes used with alternating-current circuits. The **compensator** is a device used in connection with the voltmeter to decrease the voltmeter reading as the load

increases, by an amount proportional to the drop in the line. The attendant then increases the field excitation of the alternator and brings the pressure up to such an amount that the voltage at the distributing point is correct.

Fig. 24 shows the connections for one of the earlier types of Westinghouse compensating voltmeter. It consists of a series-transformer with both primary and secondary coils wound in sections. The primary is in series with the main circuit, and the secondary connects to a small auxiliary coil *c* on the voltmeter in such a manner that the current in *c* opposes the action of the current in the regular voltmeter coil *d* that

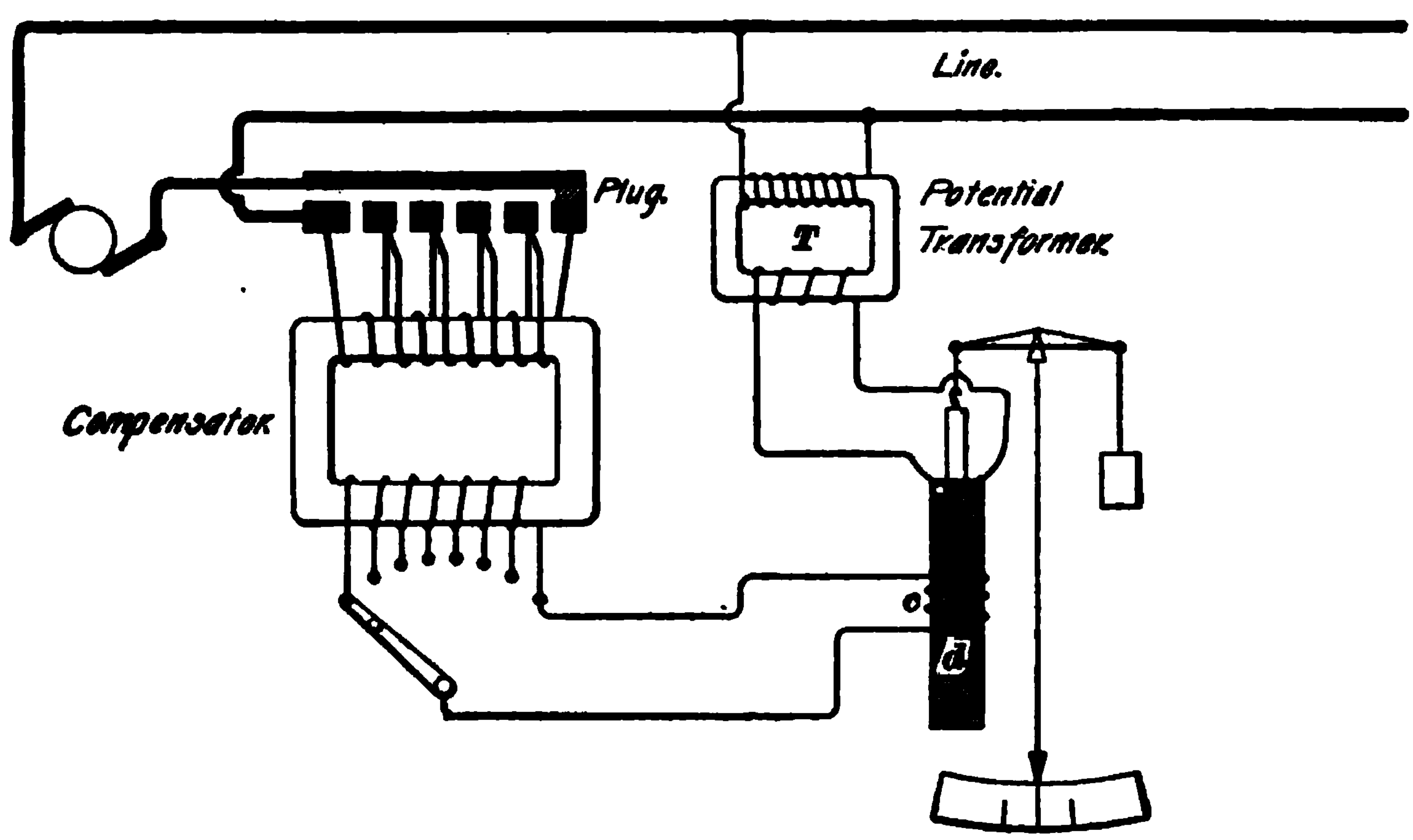


FIG. 24

is fed from the small potential transformer *T*. When the voltage at the distributing end of the line is at its correct value, the hand of the voltmeter indicates the standard voltage. When the load increases, the current through the primary of the compensator also increases; this, in turn, increases the current in the secondary and the auxiliary coil. The hand on the voltmeter, therefore, goes back, and the pressure must be raised to bring it back to the standard point. By plugging in at different points on the primary and by setting at different points on the secondary, the compensator may be adjusted for operation on almost any of the circuits

ordinarily met. After it is once set to suit the particular line on which it is to work, it requires no further attention.

25. The Mershon Compensator.—The compensator just described answers very well for lines that have little self-induction and that supply a non-inductive load. Where, however, the load is inductive, as, for example, a load of motors or of motors and lamps, the reactance of the line may have a very great influence on the drop in voltage, and the compensator must compensate not only for the ohmic drop in the line, but also for the drop due to the reactance. The **Mershon compensator,** brought out by the Westinghouse Company, is designed to accomplish this.

26. The principle of this compensator is briefly as follows: The E. M. F. supplied at the end of the line is always equal to the resultant difference between the E. M. F. generated and the E. M. F.'s necessary to overcome the resistance and reactance. If, then, three E. M. F.'s are set up at the station that are proportional to the above three E. M. F.'s and bear the same phase relation with regard to one another, and if these E. M. F.'s are combined in the same way as the line E. M. F.'s, it is evident that their resultant will make the voltmeter indicate the E. M. F. at the end of the line. For example, take the simple case shown in Fig. 25 (*a*). *A* is an alternator supplying current to the line. *T'* is an ordinary potential transformer, the secondary of which gives a voltage proportional to the generator voltage and in step with it. If the voltmeter *V* were connected directly to *T'*, it would evidently indicate the station voltage, but what is wanted is an indication of the voltage at the far end of the line, and in order to get this, the voltage of *T'* must be reduced by an amount equal to the sum of the drops caused by the reactance and resistance. An adjustable reactance *a* and an adjustable resistance *b* are therefore inserted in the circuit. The drop through *b* will be proportional to and in phase with the resistance drop, and the voltage across *a* will be proportional to and in phase with the inductive drop. From the way in which the connections are

made, it is easily seen that the voltage acting on V is a combination of the voltages of T', a, and b. The drop across a and b will increase as the current in the line increases;

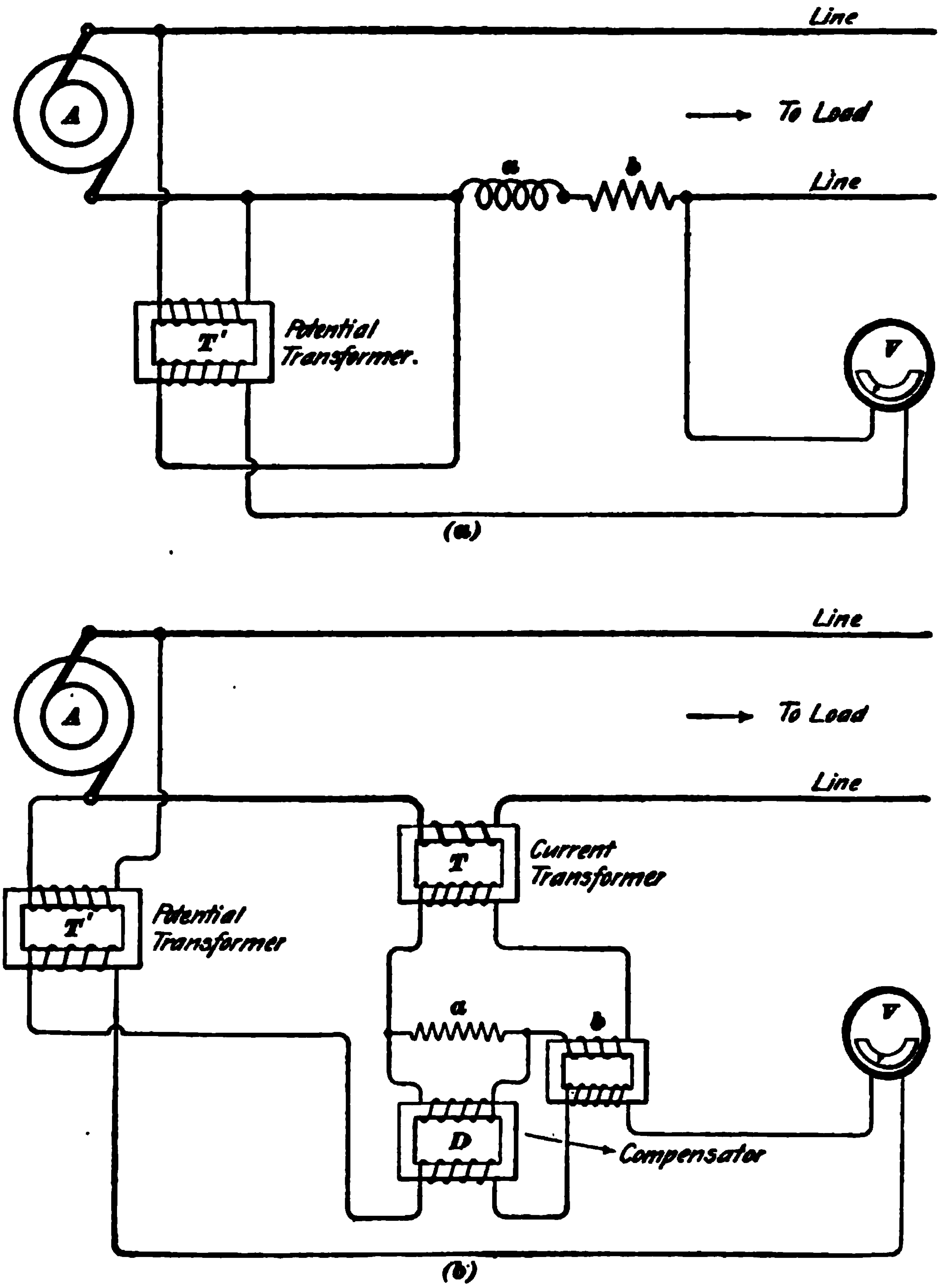


FIG. 25

hence, the voltmeter reading will decrease (because the connections are made so that the pressures across a and b cut down the E. M. F. applied to V). The voltmeter will,

therefore, indicate the true pressure at the end of the line because both the ohmic and inductive drops are accounted for.

Fig. 25 (*a*) is intended to illustrate the principle only; the actual connections are more nearly as indicated in Fig. 25 (*b*). Here *A* is the alternator, as before, and *T'* the potential transformer. *T* is a small current transformer, the primary of which is connected in series with the line and the secondary to the compensator proper, which consists of three parts, *a*, *b*, and *D*. The E. M. F. generated in the secondary of *T'* is proportional to and in step with the generator E. M. F. The current in the secondary of *T* is proportional to the load; *a* is a non-inductive resistance and *b* is a reactance coil wound on an iron core. These coils are connected in series, and the current supplied from the secondary of *T* passes through them. The E. M. F. across *a* is therefore in step with and proportional to the resistance drop in the line; while that across *b* is in step with and proportional to the back E. M. F. due to the reactance of the line. *D* is a small transformer in shunt with *a*; its secondary E. M. F. is in step with and proportional to the E. M. F. across *a*; *b* is also provided with a secondary that gives an E. M. F. in step with and proportional to the E. M. F. across *b*. All these devices, i. e., *a*, *b*, and *D*, are in one piece of apparatus, and terminals from the secondaries of *D* and *b* are brought out to two multipoint switches, so that the number of turns in each may be adjusted to suit different lines. For three-phase circuits, *a* and *b* are supplied from two series-transformers whose primaries are connected in series with two of the lines and whose secondaries are in parallel. The voltmeter compensator made by the General Electric Company operates on practically the same principle.

FUSES AND CIRCUIT-BREAKERS

27. Either *fuses* or *circuit-breakers* may be used to protect the generators or circuits from an excessive flow of current, due either to a short circuit or overload. Fuses are not used as much as they once were, as it has been found that circuit-breakers are more reliable. The

circuit-breaker may be a separate device, or the main switch may be provided with an automatic tripping device, as already described.

FUSES

28. A **fuse** consists of a strip or wire of fusible metal inserted in the circuit, and so proportioned that it will melt and open the circuit if the current for any reason becomes excessive. Fuses are often made of a mixture of lead and bismuth, though copper and aluminum are also used. Aluminum is used very largely for high-tension fuses.

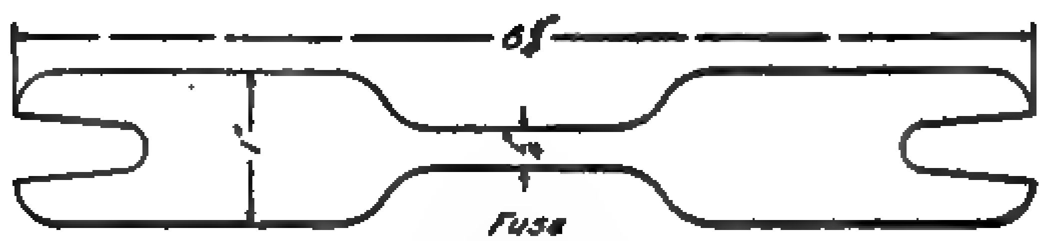
For low-tension switchboards, plain open fuses may be used; but for high-tension work, it is necessary to have them arranged so that the arc formed when they blow will not hold over. Moreover, it is necessary to have high-tension fuses arranged so that they can be renewed without danger to the switchboard attendant.

29. Fig. 26 (*a*) shows a type of fuse block used by the General Electric Company on alternating-current switchboards; (*b*) shows the shape of the aluminum fuse used in the block. The fuse holder is made in two parts, the lower part *A* being of porcelain and the upper part *B* of lignum vitæ. The lower part is provided with blades *c* that fit between the clips *d*, *d'*, in the same way as the blades of a knife switch. These clips lie in slots in the marble board *F* and are connected to the line and dynamo by means of terminals *g* and *h*. By adopting this arrangement, the whole block may be detached from the board by simply pulling it straight out, thus pulling the blades out of the clips. The fuse is shown at *l*, and is clamped by means of the screws *m*, *n*. A vent hole *p* is provided in the lignum-vitæ cover, and the rush of air through this vent, together with the confined space, results in the suppression of the arc. This fuse block is suitable for currents up to 150 amperes at 2,500 volts. For higher pressures fuse blocks are used in which the fuse is pulled wide apart as soon as it blows, thus breaking the arc.

The use of the fuses on low-tension lighting switchboards

is not as common as it once was, their place being taken by the automatic circuit-breaker. Fuses are, however, used considerably on alternating-current boards and also for protecting individual circuits on low-tension, direct-current boards. They are not as convenient or reliable as circuit-breakers, because it takes time to replace them when they blow, and only too often they are replaced with a heavier fuse or even a copper wire, which is of scarcely any use as a protection. Again, fuses of the same size do not always blow at

(a)



(b)

Fig. 26

the same current, as much depends on the nature of the fuse-block terminals. If the clamps are not screwed up tightly, local heating will result, and the fuse will blow with a smaller current than it should. Also, it has been found that a fuse of a given cross-section and material will carry a heavier current when the distance between the terminals is short than when it is long, on account of the conducting away of the heat by the terminals.

30. Fig. 27 shows a type of high-tension enclosed fuse made by the Stanley Electric Company. The fuse is held in the holder *a*, which can be pulled out of the clips *b* when a

fuse is to be renewed. Suitable blades are provided at each end to engage with clips *b*. The clips and connecting studs are thoroughly insulated by the porcelain insulators *c*, *c*, which prevent leakage of current to the supporting panel *d*. The fuse *h* passes through a fiber tube *e* and is held at each end by screws *i*; tube *e* is enclosed in the hard-rubber tube *f* of large diameter. At each end of the fuse is a cavity in which

Fig. 27

is placed a carbon ball *g*, and when the fuse blows the balls are forced up against the openings leading to the terminals, thus cutting off the arc. These fuses can handle a current of 50 amperes at 20,000 volts. There is a small hinged lid *k* on top that is thrown up when the fuse blows, and thus acts as an indicator to show which fuse has blown.

The high-tension fuse used by the Westinghouse Company consists of two long hinged wooden arms that are held together by the fuse against the action of a spring. As soon as the fuse melts, the arms separate, thus placing a break of several feet in the circuit and rupturing the arc.

CIRCUIT-BREAKERS

31. Some circuit-breakers have already been described in connection with high-tension switches. The **circuit-breaker** is essentially an automatic switch that opens the circuit whenever the current exceeds the allowable limit. It is therefore intended more as an automatic safety device than as a switch for regularly opening or closing the circuit.

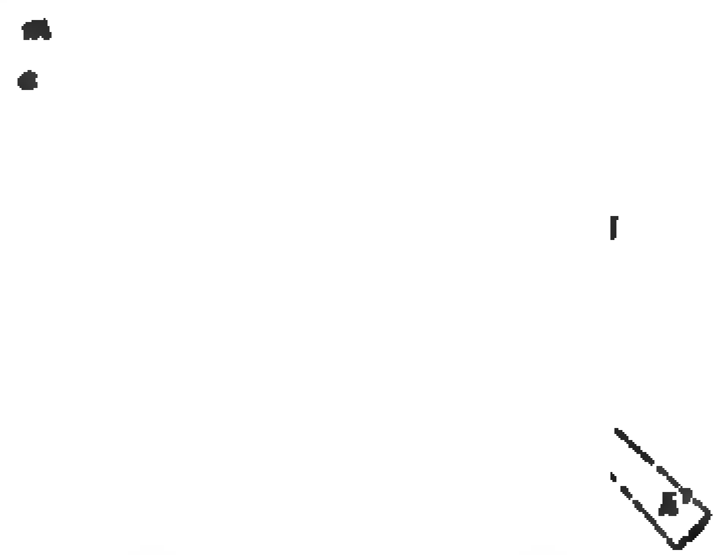


FIG. 28

Circuit-breakers are made in great variety, handling currents from a few amperes up to several thousand, and are constructed for both alternating current and direct current. In nearly every case they consist of a switch of some kind that is held closed against the action of a spring. The main current passes through an electromagnet or solenoid, and when the current for which the breaker is set is exceeded, this magnet attracts an armature or core and operates a trip, thus allowing a switch to fly out. In some cases the breaker

opens both sides of the line, though often they are single-pole and open one side only. We will illustrate here a few examples to show their general method of operation.

32. General Electric Circuit-Breakers.—Figs. 28 and 29 show a type of **General Electric circuit-breaker** designed for 125- or 250-volt circuits. One of the principal features of this circuit-breaker is the main contact used. It consists of a U-shaped laminated contact *a* which is pressed firmly against the contacts *b*, *b* by means of a togglejoint, when handle *h* is forced down. Each main contact is provided with a pair of light auxiliary contacts *m*, *m* that can be easily renewed. These wipers press against the carbon blocks *p*, *p*, and when the breaker flies out, the arc is finally broken between the carbon blocks and the wipers. Laminated contacts are not liable to stick and they make a very good contact because of the firm pressure and the slight wiping action caused by the closing of the breaker. The tripping coil *S* attracts the armature *A* when the current becomes excessive and trips the breaker, which is promptly opened by the spring *t*. The current for which the breaker is set may be adjusted by means of the screw *v* and the breaker may be tripped by hand at any time by pulling down on the knob *w*. The breaker shown in Fig. 28 is a double-pole; Fig. 29 shows a similar breaker of the single-pole type.

FIG. 29

33. General Electric M K Circuit-Breaker.—This breaker, Fig. 30, has been very widely used for 500-volt, direct-current, railway switchboards and is here shown as an example of the class of circuit-breakers in which a magnetic field is used to extinguish the arc. In Fig. 30, *B* is a heavy tripping coil through which the main current passes. The

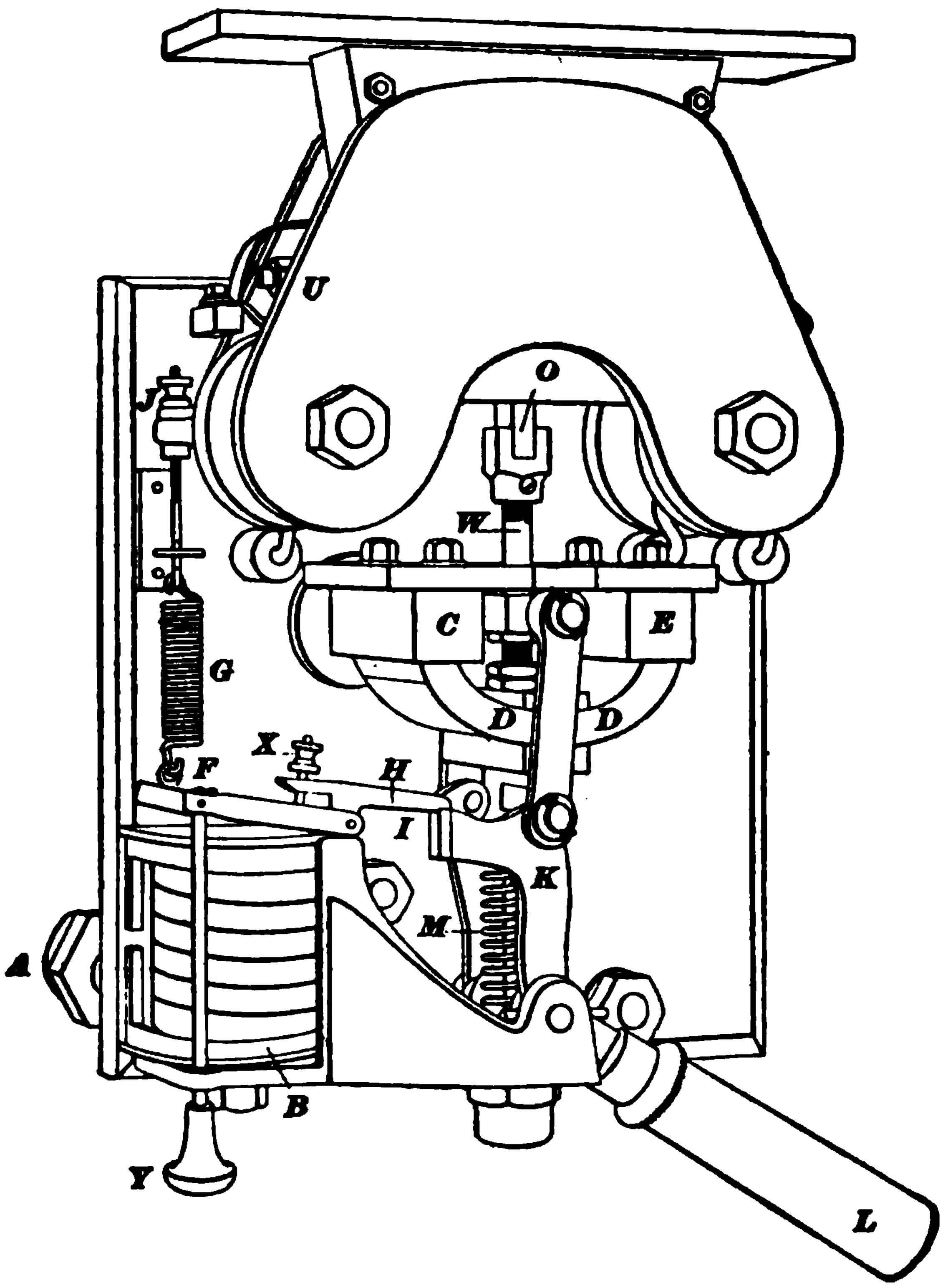


FIG. 30

current enters the coil through the stud *A*; from the coil it passes to a connection on the back of the heavy copper contact block *C*. When the breaker is closed ready for service, as shown in the figure, the main current passes from *C* to the laminated contact *D*, *D* and out to the line through the heavy block *E*, which has a terminal like *A* in the rear.

When the breaker is closed, the hinged iron armature *F* is held up by a spring *G*, the tension of which depends on the adjustment of a thumbscrew *J*. Attached to plate *F* is a trigger *H*, that has a shoulder against which a projection on the main handle yoke *K* bears. To set the breaker, the main handle *L* is pulled down hard; this forces *D*, *D* up against blocks *C* and *E*, and also causes the projection on *K* to engage trigger *H*, which holds the circuit-breaking parts in place. In setting the switch, spring *M* is extended. When the breaker trips, solenoid *B* draws down armature *F*, and with it trigger *H*, which liberates the switch yoke and allows

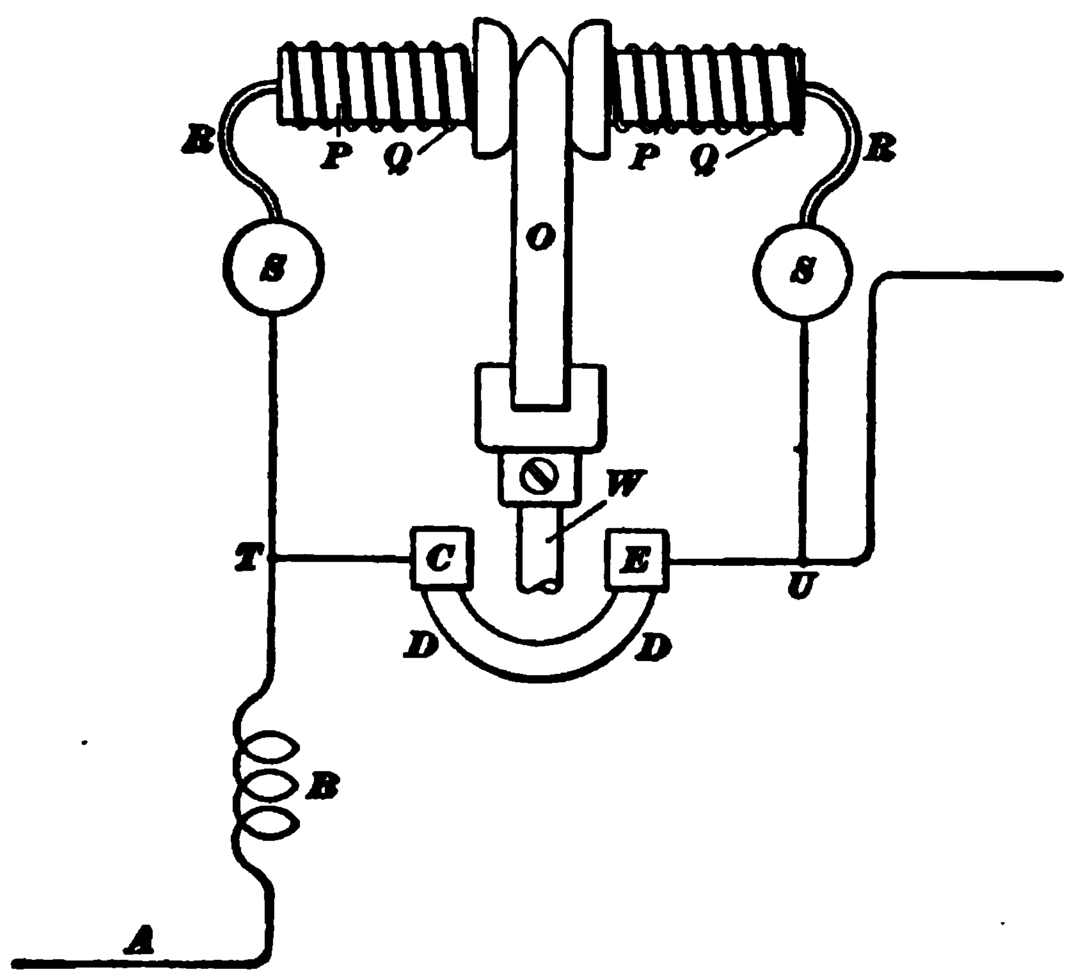


FIG. 31

the strong spring *M* to pull down *D*, *D*, and hence open the circuit at *C* and *E*. In order to prevent burning of the main contacts, a shunt path is provided, as indicated by the circuit *T-S-R-P-O-P-R-S-U*, Fig. 31. *S*, *S* are two magnetizing coils that set up a strong magnetic field between the auxiliary contacts *P*, *P*. When the breaker is closed, the contact piece *O* is pushed up between contacts *P*, *P* which are pressed firmly against *O* by springs *Q*, *Q*. When the breaker trips, contact *D*, *D* leaves *C*, *E* a little

before O leaves P, P, so that for a short interval the main current takes the path through the auxiliary contacts and blow-out coils S, S. A strong magnetic field is thus set up and when the circuit is finally broken at the auxiliary contacts, the arc is instantly blown up through an opening in the top of the breaker. Whatever burning action there may be is thus tranferred to the auxiliary contacts, which are easily renewed or repaired.

34. Cutter Circuit-Breaker.—Fig. 32 shows the **Cutter (I. T. E.) laminated-type circuit-breaker.** The main contact *a* is laminated and is pressed against the contact surfaces by means of the handle working through a togglejoint at *c*. The tripping coil is shown at *d* and when the current exceeds the amount for which the breaker is set the core inside *d* is suddenly drawn up, thus striking a trigger and allowing the breaker to fly out. The position of the core in *d* can be changed by adjusting screw *e*, thereby varying the current at which the breaker trips. Auxiliary carbon contacts *b*, *b* do not open until after the main contact so that the burning action is confined to the carbon contact surfaces. The Westinghouse circuit-breakers are very similar in general appearance and operation to the type shown in Fig. 32, the main difference being in the arrangement of the tripping coil.

Fig. 32

GROUND DETECTORS

35. Ground detectors are used to determine whether or not a line or conductor, that should normally be insulated, is in contact with the ground or any conductor leading to the ground. A voltmeter makes a very good ground

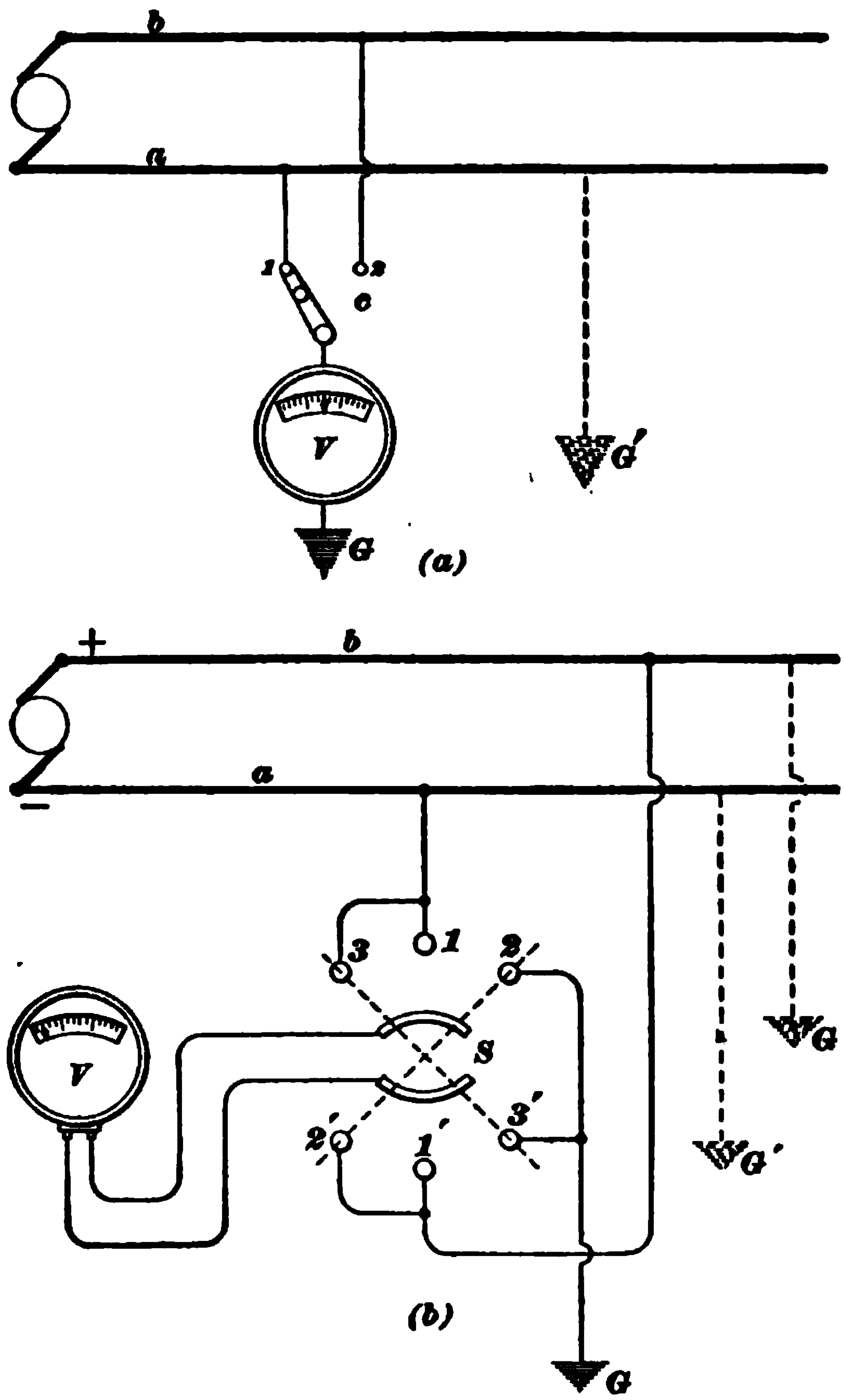


Fig. 33

detector, because it not only indicates whether a ground is present, but by its deflection it shows whether the path of the current to ground is one of high resistance or low resistance.

In order to indicate grounds, the voltmeter may be connected as shown in Fig. 33 (*a*). If the line *a* should be grounded, as indicated by the dotted line, and the switch blade placed on point *1*, no deflection would result. If, however, the blade is moved to point *2*, current will pass from line *a* through the ground on the line to the voltmeter to point *2*, and thence to the line *b*, thus completing the circuit. When a deflection is obtained on point *2*, it shows that line *a* is grounded; and when obtained on point *1*, it shows that line *b* is grounded. If the ground is of high resistance, the deflection will be comparatively small; if of low resistance, the deflection will be large. In Fig. 33 (*a*), the current will flow through the voltmeter in the opposite direction on point *2* from what it will on point *1*; hence, the voltmeter must have its zero point in the center of the scale, so that it can read either way. Voltmeters, however, have their zero point at the left-hand end of the scale, and it is convenient to have a switch that will allow the ordinary voltmeter to be used either as a voltmeter or ground detector. Fig. 33 (*b*) shows an arrangement for doing this. When the switch is in the position *1–1′*, the voltmeter *V* is connected directly across the line and gives the voltage on the system; when in the position *3–3′*, the voltmeter indicates any grounds, such as *G″*, that may be present on line *b*. When *S* occupies the position *2–2′*, *V* indicates grounds on line *a*, as at *G′*.

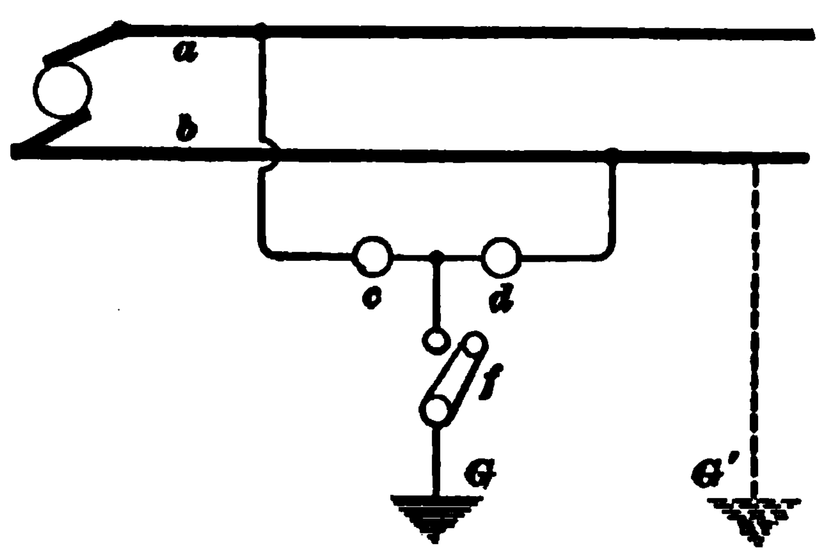


Fig. 34

36. Another very common arrangement for detecting grounds is shown in Fig. 34, where two lamps *c*, *d* are connected in series across the lines. The voltage for which these lamps are designed is equal to that of the dynamo, so that when the two are connected in series, they will burn dull red. At the point between the lamps, a connection is

made to ground through a switch or a push button *f*. If contact is made at *f* and there is no ground on either line, the brilliancy of the lamps will not be altered. If there is a ground on *b*, as indicated at G', lamp *d* will go out when switch *f* is closed, and *c* will burn brightly. This lamp detector is simple, and while it serves as an indicator of grounds, it is not as satisfactory as the voltmeter detector, as it does not give accurate indications as to the resistance of the fault.

37. Fig. 35 shows a lamp ground detector suitable for a three-wire, low-tension system. Three lamps l_1, l_2, l_3 are connected in series across one side of the system, and a ground connection is made at *x* through key *K*. When all three lines are clear of grounds, the lamps will burn at a dull red, they will all be equal in brightness, and their color will not change when key *K* is pressed. If line *C* becomes grounded at G', then, when *K* is pressed,

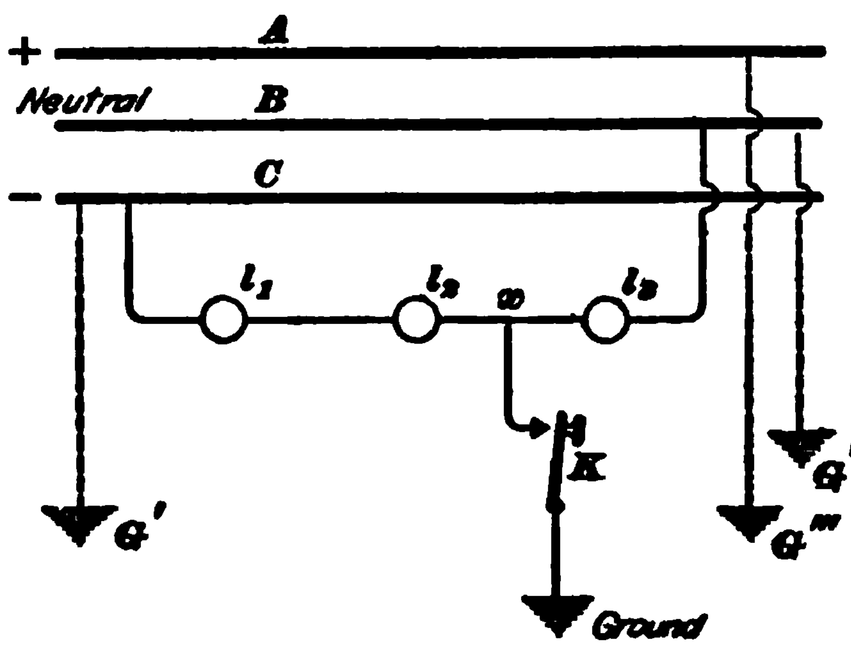


Fig. 35

l_1 and l_2 will go out, and l_3 will come up to full candlepower. If a ground occurs at G'' on line *B*, lamp l_3 will go out and l_1, l_2 will brighten up, but will not come up to full candlepower because two of them will be in series between *B* and *C*. If there is a ground at G''' on line *A*, all the lamps will come up to full candlepower, because they will all get the full voltage, l_3 being across *A B* and l_1, l_2 in series across *A C*.

38. The ground detectors just described apply more particularly to low-tension, direct-current installations, but similar arrangements may be adapted to high-tension, alternating-current systems by using potential transformers. Fig. 36 shows one method used by the Westinghouse Company on their alternating-current switchboards. The regular

voltmeter *V*, with which the switchboard is equipped, is here used also as a ground detector. *P* is a plug switch by means of which points *1* and *2* or *1* and *3* may be connected together. Under ordinary conditions, the plug is in *1* and *2*, thus connecting the primary of the potential transformer across the line, and *V* serves as an ordinary voltmeter. *S* is a key that connects one side of the line to ground through the transformer primary. If there happens to be a ground on the side *b*, as shown at *G'*, the voltmeter will give a reading when *S* is pressed. By placing the plug in points *1* and *3*, side *a* may be tested. When the key *S* is not pressed, the lever *5* is against contact *4*, so that *V* is connected as an ordinary voltmeter.

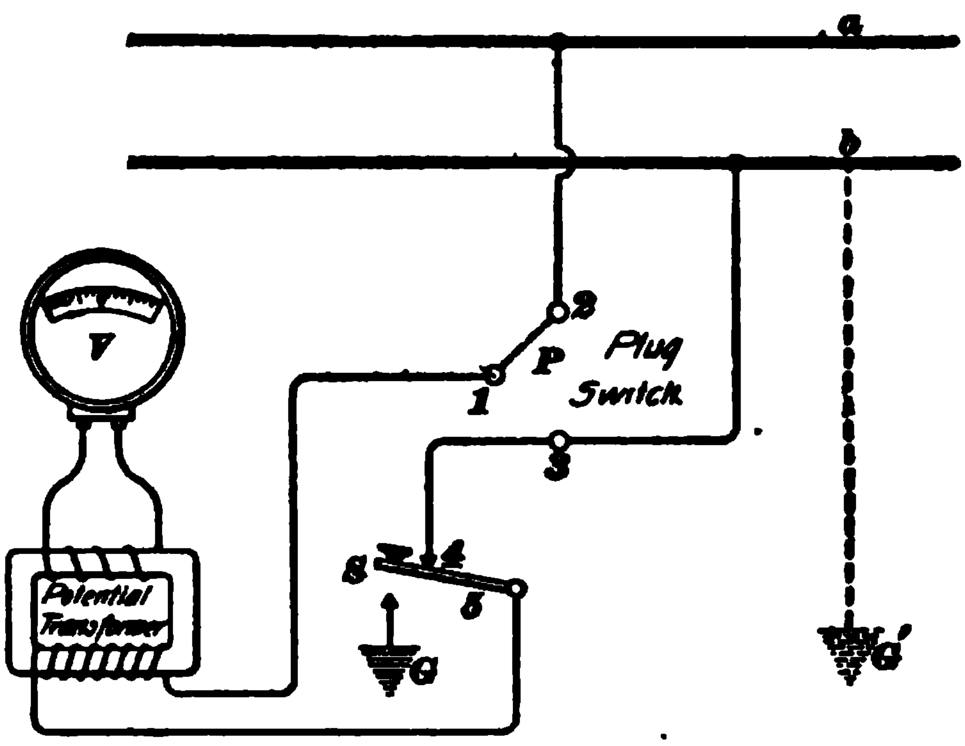


FIG. 36

39. Electrostatic Ground Detectors. — Ground detectors operating on the electrostatic principle are much used on high-pressure, alternating-current switchboards. They have the advantage that they require no current for their operation and may be left connected to the circuit all the time, thus indicating a ground as soon as it occurs. They also give an indication without its being necessary to make an actual connection between the line and ground, as is the case with all the detectors previously described. Fig. 37 illustrates the principle of a Stanley electrostatic ground detector, which is especially adapted to high-pressure, alternating-current lines because the instrument is not in actual connection with either of the lines. The fixed vanes *1* and *4*,

2 and *3* are connected together in pairs, as shown. The movable vane *V* is connected to the ground and is held in the central position shown in the figure by means of small spiral springs *S*. The pairs of fixed plates are not connected direct to the lines, but are attached to plates *a*, *a'* of two small condensers which consist simply of two brass plates, mounted in hard rubber but separated from each other. Plates *b*, *b'* are connected to the lines. When no grounds

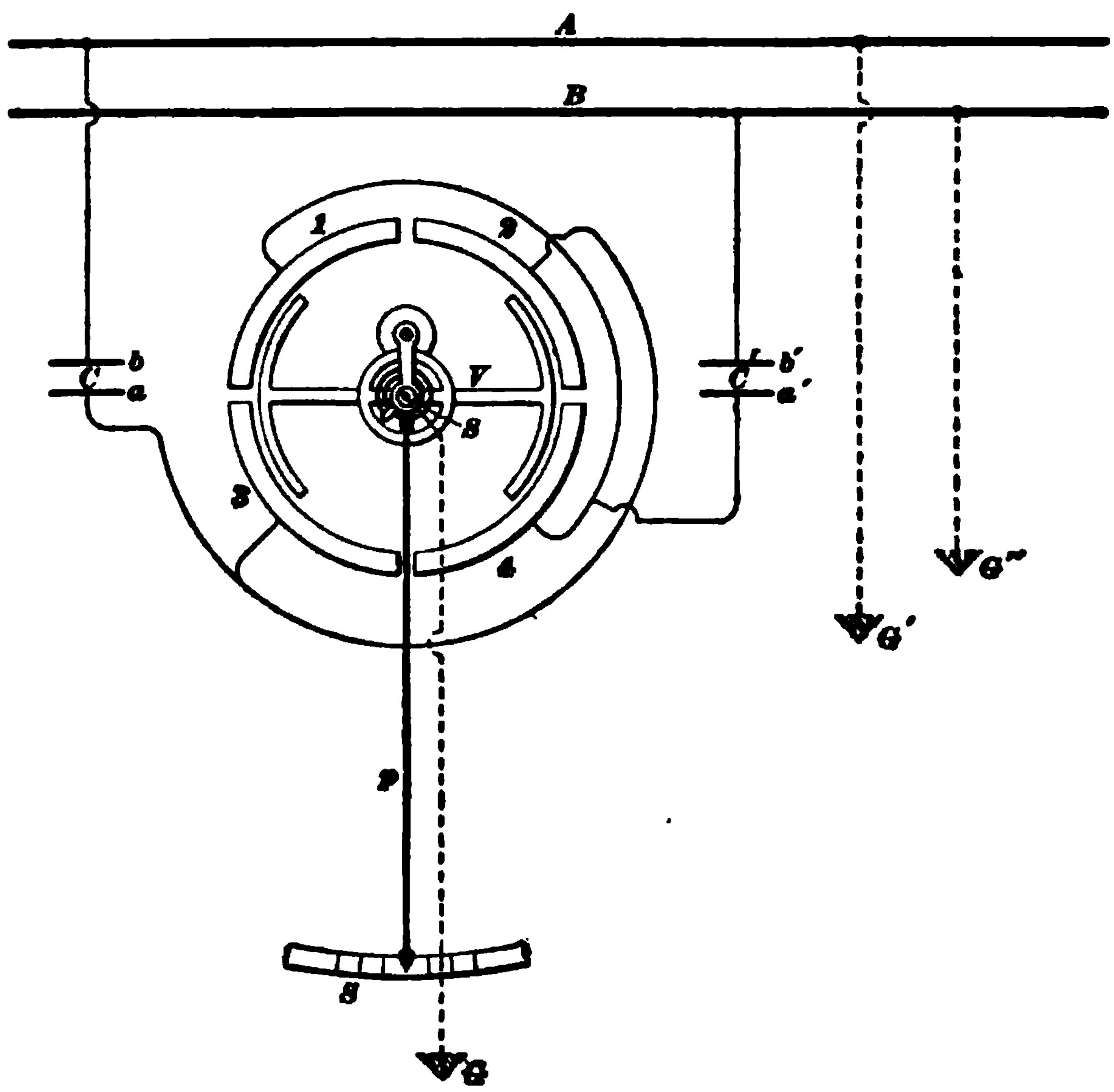


FIG. 37

are present, *1* and *4*, *2* and *3* become oppositely charged by reason of charges induced on plates *a*, *a'* by plates *b*, *b'*. At any instant the charge on vanes *1* and *4* will be similar to that on *B*; at the same time the charge on vanes *2* and *3* will be similar to that on *A*. The forces acting on the vane *V* are therefore equal and opposite. Now, suppose that line *B* becomes grounded at *G''*. This is equivalent to connecting vane *V* to line *B*; *V* takes up a charge similar to *1* and *4*; hence, it is repelled by *1* and *4*

and is attracted by *2* and *3*, thus giving a deflection. If *A* becomes grounded, a deflection in the opposite direction is obtained. Instruments of this kind can, of course, only be used in places where the pressure is fairly high, as the electrostatic forces produced by charges due to low pressures would not be large enough to operate an instrument unless it were made much too delicate to be of practical use in a light or power station. In most electrostatic detectors, the lines are connected directly to the fixed sectors *1*, *2*, *3*, *4* and the condensers *C*, *C'* are omitted.

FIG. 38

40. Fig. 38 shows an electrostatic ground detector made by the Wagner Electric Company. The fixed quadrants are shown at *a*, *a*, and the movable vane at *b*, *b*. The quadrants are connected to the line wires, and the vane is connected to ground. The vane is held normally in its central position by means of a spring, and the pointer is deflected whenever a ground occurs on either line. The principle of action is the

FIG. 39

same as that of the electrostatic ground detector just described.

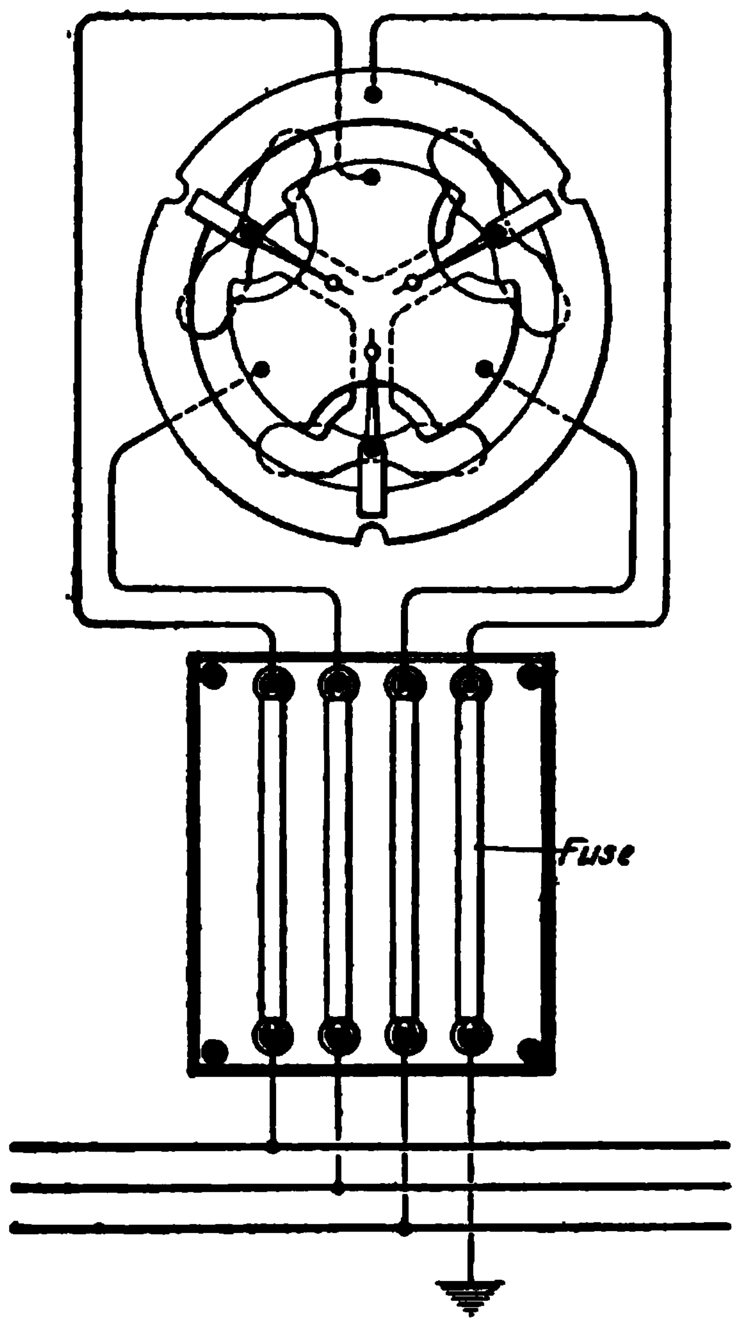


FIG. 40

41. Figs. 39 and 40 show a General Electric, three-phase, electrostatic ground detector. It is practically three single-phase detectors combined in one instrument. When no ground exists, the three needles point toward the center. When a ground occurs on one of the lines, the two adjacent needles are deflected toward the segments to which the grounded line is connected. Should a ground occur on two lines, the needle between the segments connected to the grounded lines will be deflected toward the one having the lower resistance ground and the two remaining needles will be deflected toward the grounded segments.

POTENTIAL REGULATORS

42. Where a number of feeders are supplied from a single dynamo or set of bus-bars, it is often necessary to provide means for raising or lowering the pressure on these feeders independently of each other. When alternating current is used, the pressure on the feeders can be easily adjusted by using **potential regulators.** These appliances, while not usually placed on alternating-current switchboards, are so closely connected therewith that they are here described. There are many types of regulators but they all take the form of a special type of transformer with the primary connected across the mains and the secondary in series with one of the mains.

43. Use of Transformer to Raise Voltage.—An ordinary transformer connected as in Fig. 41 can be used to raise or lower the primary voltage by an amount equal to the secondary voltage of the transformer. When the double-throw switch is in the position indicated by the dotted lines, the primary is across the mains and the secondary in series with the lower main, thus adding 100 volts in this case or subtracting 100 volts if the connections be such that the secondary E. M. F. opposes the line E. M. F. When the switch is thrown to the right, the boosting transformer is cut out.

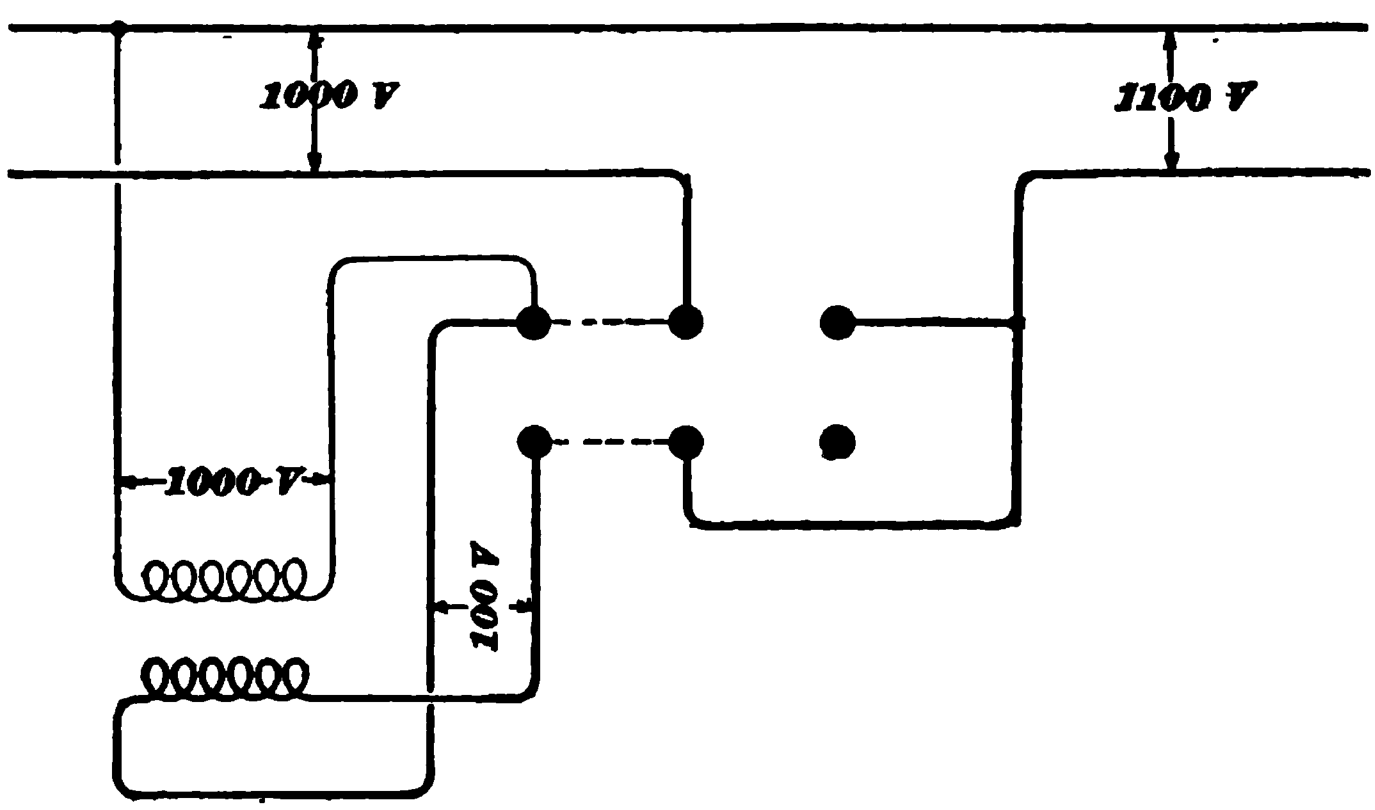


FIG. 41

44. Stillwell Regulator.—Fig. 42 shows the connections for a **Stillwell regulator.** It operates in the same way as the transformer in Fig. 41 but the secondary S is provided with a number of taps connected to a switch M so that the amount by which the voltage is raised or lowered can be adjusted. The primary P is connected to a reversing switch b so that the secondary E. M. F. can be made either to aid or oppose the primary E. M. F., thus using the regulator either to raise or lower the line pressure. The contact arm N is made in two parts, connected through a small reactance coil r, the object being to prevent momentary short-circuiting of the transformer sections during the instant the arm bridges over adjacent contact segments. By

following out the connections, it will be seen that the secondary is in series with the main circuit and the primary across the circuit, as in Fig. 41.

45. C R Regulator.—The **C R regulator,** made by the General Electric Company, operates in a manner very

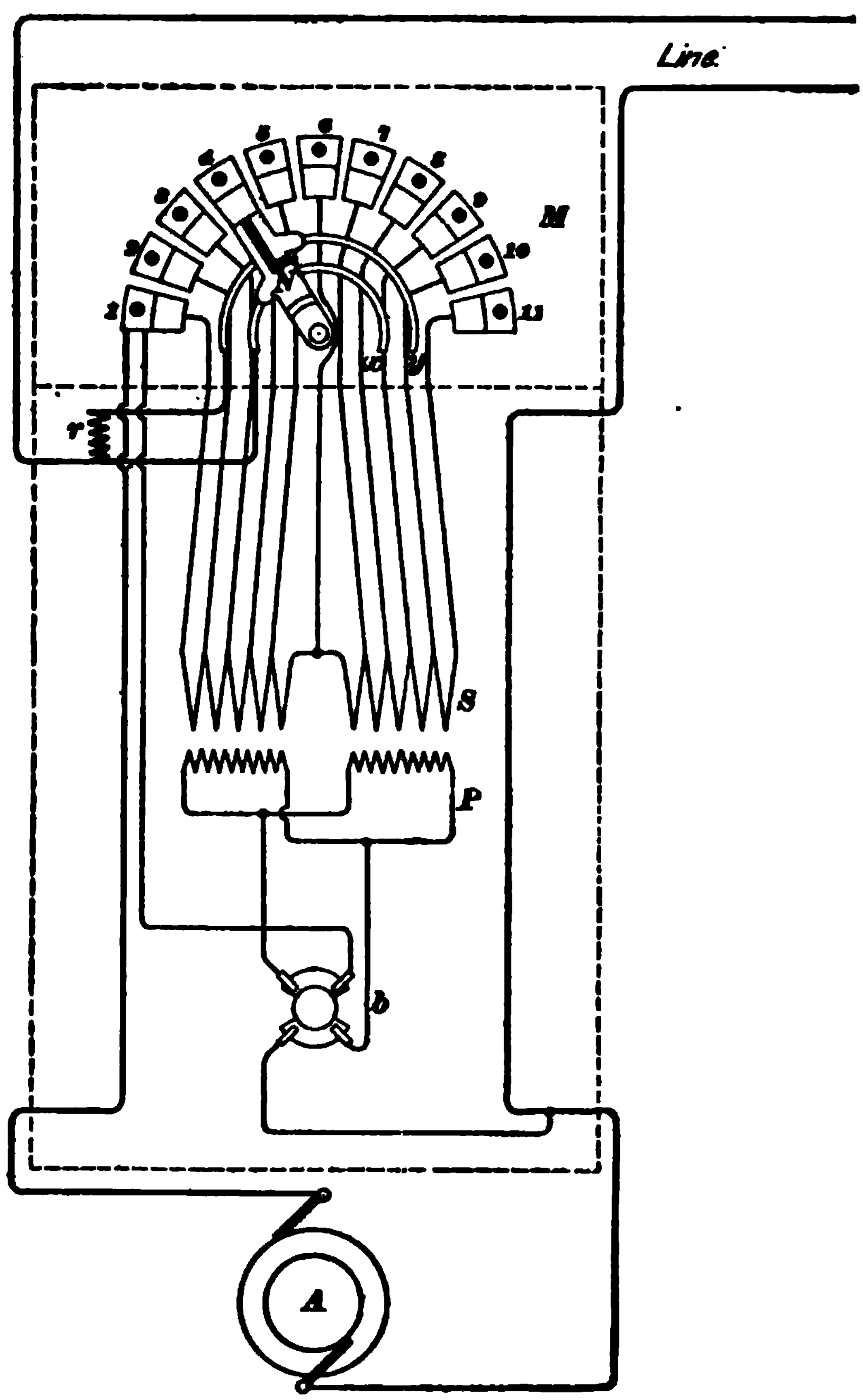


FIG. 42

similar to the Stillwell regulator. Fig. 43 shows the general appearance of the regulator, and Fig. 44 the connections. The reversing switch operates automatically and is placed in the secondary circuit, and not in the primary as in the Stillwell

regulator. In Fig. 44 the reversing switch is indicated at the lower part of the figure, and consists of an arm that is moved by the arm of the main switch so as to connect *a* with either *c* or *b*. The windings consist of a primary and secondary, the former connected across the circuit, and the latter divided into a number of steps, in series with the circuit. When the reversing switch and the main switch arm are in the positions shown in Fig. 44, the main current flows through the whole of the secondary winding, and the maximum increase in voltage is obtained. As the dial switch arm is turned, the sections of the secondary are successively cut out as contact is made at *d*, *e*, *f*, etc.; when the arm reaches *g*, the whole of the secondary winding is cut out, and the voltage supplied to the feeder is the same as that furnished by the generator. When the arm is started on a second right-handed

FIG. 43

FIG. 44

revolution, the reversing switch is shifted automatically, so that point *a* is connected with *b*, and as the movement of the dial switch is continued to the right, the sections of the secondary are successively cut in, and the current now flows through them in the reverse direction to what it did before. The second revolution, therefore, lowers the feeder pressure below that of the generator; when the second revolution has been completed, the switch is automatically stopped. The dial switch is made so that when the handle is turned, springs are first compressed and the blade then unlocked by a cam so that it flies from one contact to the next almost instantly. The switch blade is slightly narrower than the distance between the contacts, so that there is no short-circuiting of the transformer sections.

46. A number of regulators are in use in which the voltage in the secondary is varied by changing the position of the secondary with regard to the primary, instead of cutting turns in or out. By having the secondary coil movable, it can be arranged so that the amount of magnetic flux passing through it can be varied, thus varying the amount of the pressure added or subtracted. In other regulators, both the primary and secondary coils are fixed, and a movable core arranged so that the magnetic flux passing through the secondary can be made to vary.

PROTECTION FROM LIGHTNING AND STATIC CHARGES

47. There are sources of danger to electrical equipments that may arise outside the station and that may cause great loss unless ample provision is made for protection. Among these are danger from lightning, danger from static charges, or other effects commonly referred to as *static*, and danger from short circuits caused by either of the former. Damage from lightning occurs on systems having overhead lines, but static charges and the damage resulting therefrom can occur on systems having either overhead or underground lines.

PROTECTION FROM LIGHTNING

48. Damage from lightning is due to an excessive difference of potential that may exist between the atmosphere and the earth, and as overhead electrical conductors offer a path of comparatively low resistance, the atmospheric electricity will seek such path to the earth, unless prevented by suitable methods of lightning protection. Any properly designed piece of apparatus should have sufficient insulation to withstand a potential considerably higher than that normally imposed on it, and to produce a ground, a lightning discharge must cause an excessive rise in the potential of the circuit. It frequently happens that the weakest point of insulation is at the switchboard or generator, and in the absence of sufficient protection, great damage will result at the station.

49. Overhead lines are always liable to accumulate a certain charge of static electricity even if they are not actually struck by lightning. Long transmission lines should be well protected against lightning, as they frequently run through exposed and mountainous country. If these high-pressure discharges travel along the line and get into the

dynamos at the power station, they are almost sure to puncture the insulation of the machines and cause a burn-out. To guard against this, *lightning arresters* should be provided.

50. Simple Lightning Arrester.—The term **lightning arrester** does not correctly express the use of these devices, because they do not arrest the discharge coming in over the line; they merely divert the charge by providing a path that the lightning will take to ground in preference to passing into the dynamo and making a path for itself to the ground by puncturing the insulation of the machine.

A lightning discharge is generally oscillatory in character, hence it will not pass through an inductive path if an

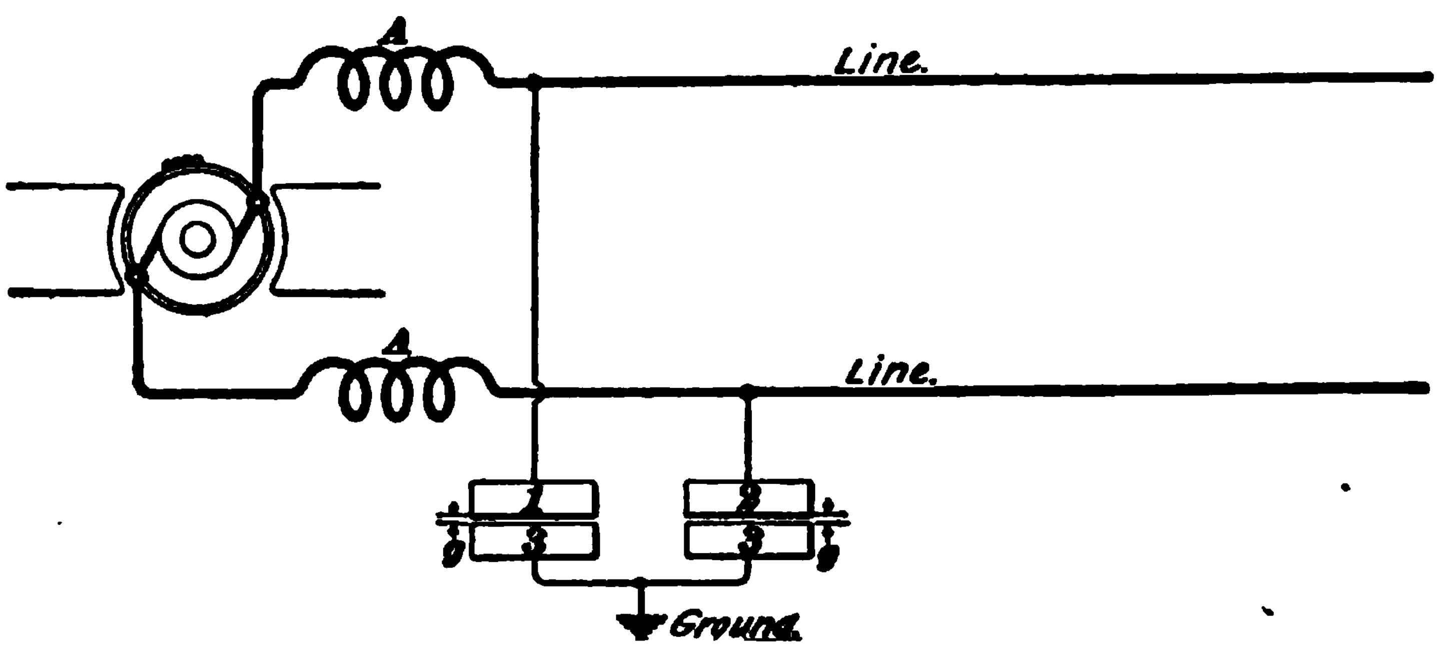


FIG. 45

alternative non-inductive path is provided for it. The object of a lightning arrester is to furnish a non-inductive path to ground and at the same time make provision for suppressing the arcing that usually follows a discharge. Fig. 45 shows a line equipped with lightning arresters of the simplest possible form. The plates *1*, *2* are connected to the lines and are separated by small gaps *g*, *g* from plates *3*, *3* which are connected to the ground. The gap in the arrester should be more easily jumped across by the discharge than the weakest insulation on the dynamo; otherwise, the discharge may jump through the insulation to the ground instead of jumping across the air gap. The air gap must, of course, be long enough so that the pressure generated by the dynamo

itself will not be able to jump across it. For pressures up to 500 volts, a gap of $\frac{1}{16}$ inch should be sufficient.

51. Reactance, or Choke, Coils.—In order to force the discharge to pass through the arrester, **choke coils, reactance coils,** or **kicking coils,** as they are variously called, are inserted between the arrester and the device to be protected. Such coils consist of a few turns of wire or copper strip connected in the circuit as shown at *A, A* in Fig. 45. The discharge, in preference to overcoming the inductance of these coils, will jump the air gaps and pass off to ground. Fig. 46 shows a typical reactance coil of small size suitable for low-tension work. Fig. 47 shows a Westinghouse choke coil made of flat copper ribbon and mounted on a heavy glass insulator. This coil is for use on a high-tension circuit; hence, thorough insulation from the ground is necessary.

FIG. 46

52. Suppression of Arcing.—The simple arrangement of air gaps shown in Fig. 45 would not be suitable for electric-light and power circuits for the following reason: If a discharge comes in over both the lines at once, as is quite likely to happen, because the lines usually run side by side, an arc will be formed across both the gaps, and current from the dynamo will follow the arc. This will practically short-circuit the dynamo, and such a large current will flow that the plates or contact points of the arrester will be destroyed. It is necessary, then, to have in addition to the air gap some means for suppressing or blowing out the arc as soon as it is formed. It is also necessary that as soon as the discharge has passed, the arrester will be in condition for the next discharge. Generally speaking, the arc from a direct-current machine is not as easily extinguished as that from an alternator; probably because every time the current passes through its zero value it loses some of its ability to hold the arc. In some cases, the arc is broken by being drawn out

until it can be no longer maintained; in others, the air gap is so placed that it will be surrounded by a magnetic field, so that when the arc is formed it is forced across the field and stretched out until it is broken. Another method is to make the arc occur in a confined space so that it will be smothered out. Still another method is to make the cylinder or plates between which the arc jumps of a so-called non-arcing metal, the vapor of which offers a high resistance to the discharge. Some arresters will work on either direct or alternating current; but, generally speaking, the arrester has to be selected with reference to the voltage of the circuit on which it is to be used and also with reference to the kind of current.

53. Ground Connections for Lightning Arresters. Arresters will be of little or no use if good ground connections are not provided for them. The following methods of making ground connections are recommended by the Westinghouse Company: A ground connection for a line or pole lightning arrester is shown in Fig. 48.

FIG. 47

A galvanized-iron pipe is driven well into the ground and the top of it surrounded by coke, which retains moisture; the wire is run down the pole and connected to the top of the pipe as indicated. The wire is sometimes incased in galvanized-iron pipe for about 6 feet from the base of the pole and if this is done, it is well to solder the ground wire to the pipe at *a*. The following method of making the ground connections at the station is recommended: A hole 6 feet square is dug 5 or 6 feet deep in a location as near the arresters as possible,

preferably directly under them. The bottom of this hole is then covered with charcoal or coke (crushed to about pea size) to a depth of about 2 feet. On top of this is laid a tinned, copper sheet, about 5 feet by 5 feet, with the ground wire (about No. 0 B. & S.) soldered completely across it. The plate is then covered with a 2-foot layer of coke or charcoal and the remainder of the hole filled with earth, running water being used to settle it. This will give a good ground, if made in good, rich soil; it will not give a good ground in rock, sand, or gravel. Sometimes grounds are made by putting the ground plate in a running stream. This, however, does not give as good a ground as is commonly supposed, because running water is not a particularly good conductor and the beds of streams very often consist of rock. When lightning arresters are installed, all wires leading to and from them should be as straight as possible. Bends act more or less like a choke coil and tend to keep the discharge from passing off by way of the arrester.

FIG. 48

ARRESTERS FOR DIRECT CURRENT

54. Garton Arrester.—Fig. 49 illustrates the **Garton arrester.** The discharge points are of carbon, shown at *h* and *j*. These are about $\frac{1}{32}$ inch apart, and the lower one is connected to ground; *f* is a coil of wire wound on the tube *g*,

closed at the top; *e* is a small core of iron attached to the rod *d*, which in turn connects, by means of a small flexible cable, to one end of a resistance *b*. The other end of the coil connects to the other end of the resistance, to which the line also connects. The resistance *b* is made up of a stick of graphite, which, having practically no inductance, offers little or no opposition to the discharge and is used to limit the rush of current that follows the discharge. The discharge comes in over the line to *a*, passes through *b* to the rod *d*, thence to the carbon point *h*, and jumps the air gap to the ground. The discharge is followed by current from the dynamo, and, since the coil is in shunt with the resistance, part of the current will flow through the coil, thus drawing up the core *e* and breaking the arc between *e* and *h*. The fact that the arc also takes place in the enclosed tube tends to put it out. As soon as the discharge has passed, the core drops back and the arrester is ready for the next discharge. This arrester can be used on either direct- or alternating-current circuits.

Fig. 49

55. Westinghouse Arrester.—Fig. 50 shows a **Westinghouse arrester** used on direct-current circuits. It has no movable parts, and the arc is extinguished by smothering it in a confined space. Two terminals *b*, *b* are mounted on a lignum-vitæ block and are separated by a space somewhat less than ½ inch. This space is crossed by a number of charred grooves, so that although the resistance in ohms between the terminals is very high, the lightning will readily leap across the space. The block *A* is covered by a second block, not shown in the figure, that excludes the air and confines the arc to the small space between the terminals.

When the arc tends to follow the discharge, the small space is soon filled with a metallic vapor that will not support combustion. It should be noted that this arrester is intended for use on direct-current circuits only, where the pressure does not exceed 600 or 700 volts.

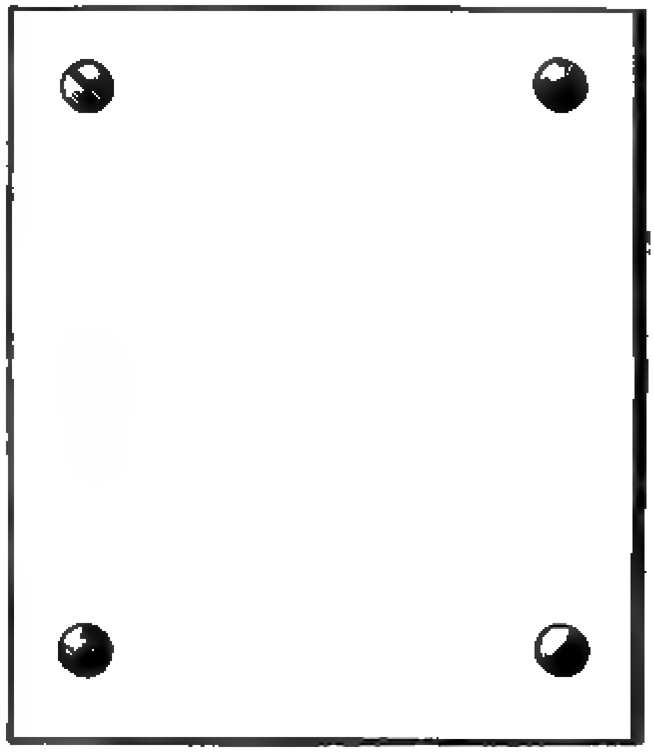
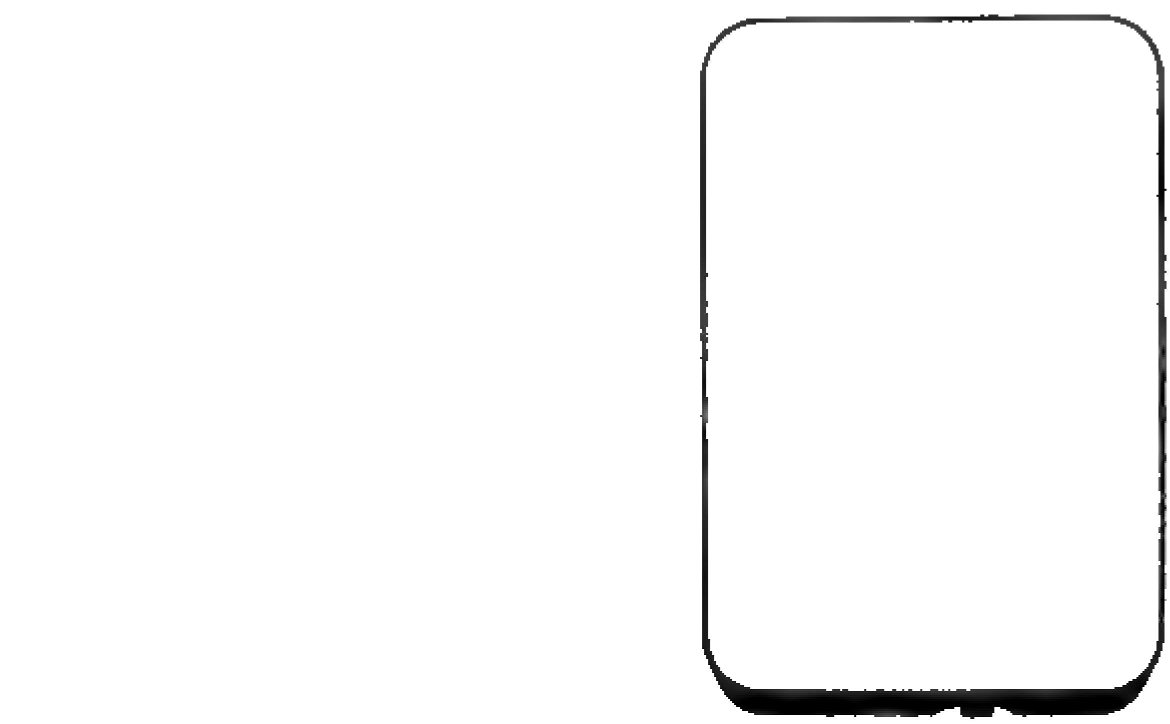


Fig. 50

56. General Electric Arrester.—In the **General Electric arresters** for direct current, the arc is blown out by making it occur in a magnetic field provided by an electromagnet. Fig. 51 shows a direct-current arrester with the cover removed; the case and cover are made of porcelain. The



(a) Fig. 51 (b)

part (*b*) holds the blow-out coil *c* with its polar projections *h*, *h*;

r is a graphite resistance for limiting the current. The electrodes are mounted in the cover and are held by clips *k*, *k'*; the air gap *a* is about .025 inch in length. When the cover is in place, clips *k'*, *k'* make contact with the tongues *k*, *k*, and give the scheme of connections shown in Fig. 52. Here *a* represents the air gap, shown also at *a*, Fig. 51 (*a*), *x y* is the blow-out coil, *r r'* the graphite resistance. The ground connection is made to the lower end *l* of the resistance, and the line is connected to the upper electrode. The terminals of the blow-out coil

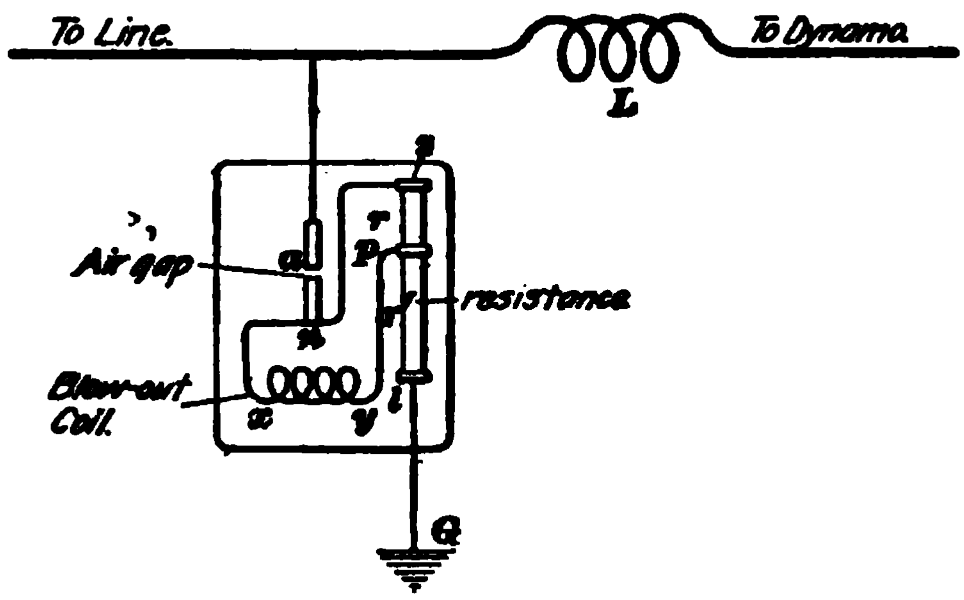


FIG. 52

connect to *z* and *p*, so that the coil is in parallel with a portion of the resistance. When a discharge comes in over the line, it jumps the air gap and passes to the ground through the resistance, and when the current follows the discharge, part of it passes through the blow-out coil. When the cover is placed in position, the air gap *a* falls between the pole pieces *h*, *h*, and the arc is blown out through an opening in the cover. A portion of the resistance *r'* is in series with the coil and spark gap, and thus limits the amount of current that tends to follow the discharge. The ordinary type of this arrester is suitable for any direct-current circuit using pressures of 850 volts or less.

ARRESTERS FOR ALTERNATING CURRENT

57. Westinghouse Arrester for Alternating Current.—Fig. 53 shows a type of arrester that has been largely used by the Westinghouse Company on alternating-current

circuits. It is known as the Wurts non-arcing arrester, and consists of a number of milled cylinders *a*, *a* separated from each other by small air gaps. The end cylinders are connected to the lines and the middle cylinder to the ground. With this arrangement, a single arrester does for both sides of the line; where, however, the line pressure is high, a separate arrester is used for each side; and for very high pressures, such as are used on long-distance lines, a number of arresters are connected in series. When a discharge comes in over the line, it jumps the gaps between the

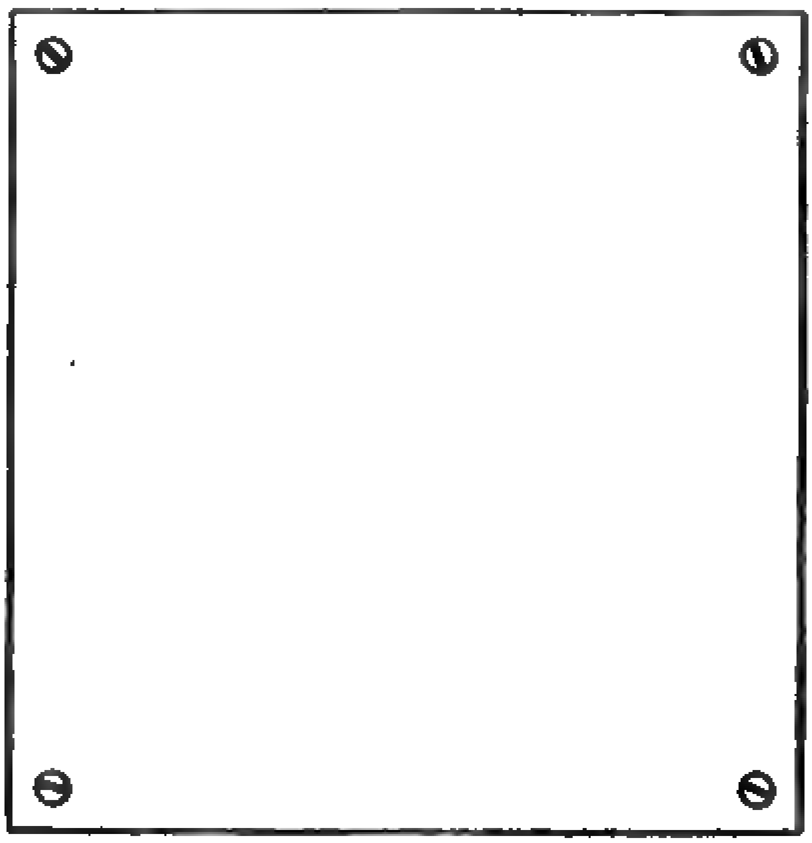


FIG. 58

cylinders and passes to the ground. It is claimed that the arc does not hold over, because the gases formed by the volatilization of the metal will not support an arc. The cylinders are made of what is known as non-arcing metal. Others claim that the suppression of the arc is due to the cooling effect of the cylinders and the alternating nature of the current. These arresters should be examined from time to time and the cylinders rotated slightly so that they will present fresh surfaces to each other.

58. General Electric Arrester for Alternating Current.—Fig. 54 shows an arrester used by the General Electric Company for alternating-current circuits. It is somewhat similar to the Wurts arrester, except that fewer spark gaps are used and a non-inductive resistance *r* is inserted in the circuit in order to limit the current following the discharge. The spark gaps *a*, *a* are between the heavy metal cylinders *b*, *b*, *b*, the middle one of which is connected to ground in the double-pole arrester shown. This arrester, like the previous one, is not suitable for use on direct-current circuits.

The arresters just described have been shown as arranged for indoor use in the station. They may, however, be used on the line, in which case they should be mounted in a weather-proof box made of iron or wood. The connections to and from the arresters should be made with wire not less than No. 4 B. & S.

Fig. 54

59. Westinghouse Arrester for High-Tension Lines.—When lightning arresters are used on high-tension lines, they usually consist of a number of air gaps connected in series between the line and the ground, the total length of air gap being so proportioned that the normal voltage of the system, even if one line becomes grounded, will not cause a current to jump across the gaps; the gaps are generally used in connection with a resistance that will prevent a rush of current after a discharge. A choke coil is also used to choke back the electrostatic wave passing along the line, and make it take the path to ground. Fig. 55 shows one of the air-gap units used with Westinghouse high-tension lightning arresters. It consists of seven knurled cylinders *a*, *a*, separated by six $\frac{1}{32}$-inch air gaps, and made of non-arcing metal.

The cylinders are arranged so that they can be revolved in the porcelain holders *b*, *b* in case the parts facing each other should be burned by the discharge.

Fig. 56 shows the connections of a **Westinghouse low-equivalent arrester** as arranged for a 6,000-volt circuit. The line to be protected is connected at point *A*. Two sets of gaps *B* and *C* are connected in series and to the ground through a series-resistance *R′*. The gaps *C* are shunted by a resistance *R* and are known as *shunted gaps;* gaps *B* are called *series-gaps*. When the potential at *A* rises to an abnormal amount due to a lightning discharge or other cause, a discharge leaps across the series-gaps *B*. If the discharge is heavy, it will meet with a large amount of opposition in the resistance *R*, and will pass over gaps *C* and resistance *R′* to ground. The current that tends to follow the discharge and that is maintained by the dynamo will take the path

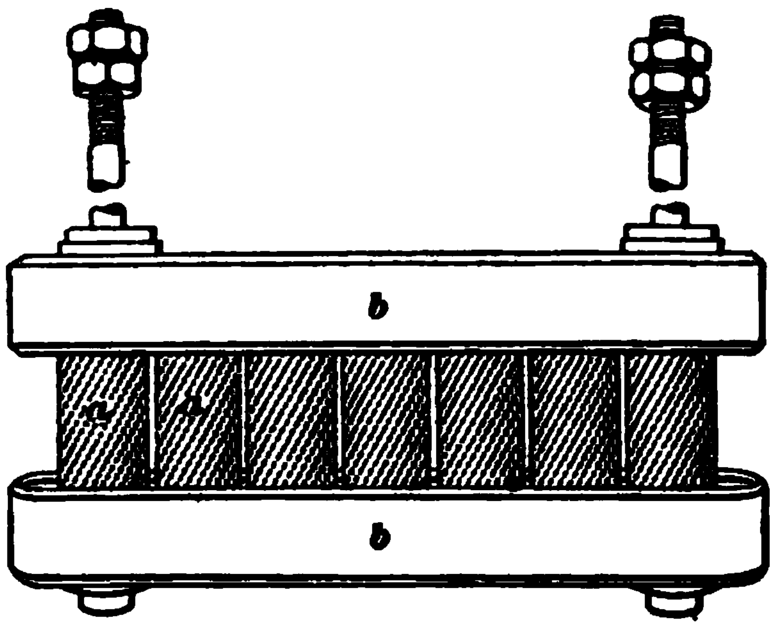


Fig. 55

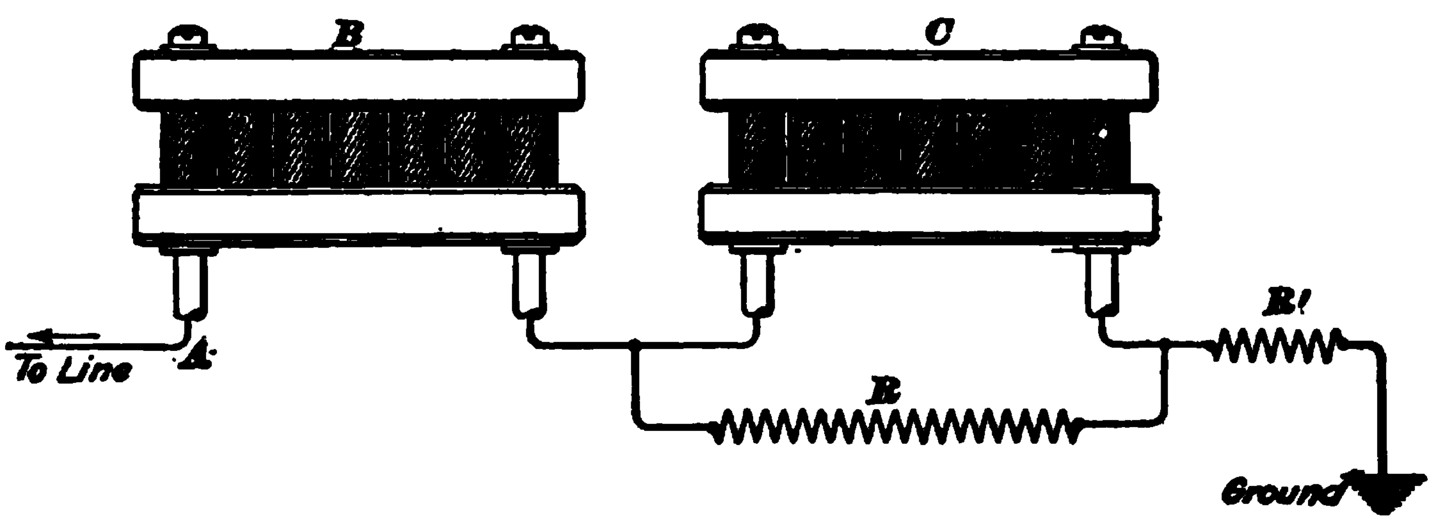


Fig. 56

through *R* instead of passing across gaps *C*, so that the effect of the shunted resistance is to withdraw the arc from gaps *C* and at the same time cut down the volume of current so that the series-gaps can suppress the arc. By using this arrangement a smaller number of gaps at *B* is needed than

would otherwise be necessary. The series-resistance R' is used to limit the initial flow of current and prevent burning of the cylinders B.

Fig. 57 shows the arrangement of one of these arresters with its choke coil. The spark gaps are at a, a, while the

To Line

To Apparatus

FIG. 57

resistances are mounted in suitable holders b, b. The arrester shown in Fig. 57 is for 8,500 volts. For arresters of higher voltage than this, the series-resistance is not mounted on the same panel with the other parts, but is placed separately on suitable columns that provide thorough insulation.

60. In the selection of lightning arresters the following points should be kept in mind:

1. The width and number of spark gaps should not be so great as to require the potential of the lightning charge to

be as high or higher than the potential necessary to rupture the insulation of the system.

2. On account of its nature, a lightning arrester is evidently exposed to severe potential strains; consequently, all live parts must be well insulated. On arresters for low voltages it is not a difficult matter to secure proper insulation, as the construction of the arrester itself affords protection. On high-tension arresters, however, proper insulation is a more difficult matter.

3. The general design and construction of the arresters, together with the necessary adjuncts, should be such as to withstand very heavy lightning discharges without destruction.

4. As current is apt to follow the slightest discharge, it is necessary that the arrester should be designed to break the arc quickly without permitting an excessive flow of current.

5. Line terminals should not be exposed in arresters in such a manner as to permit of the accumulation of dust, dirt, bugs, cobwebs, etc., which may facilitate the formation of short circuits and resulting arcs across terminals.

6. Arresters should be designed to handle heavy discharges of atmospheric electricity without permitting the same to follow the circuit and puncture the insulation of the station apparatus.

61. The importance of adequate protection becomes greater with the increased extension of the system, for the reason that the larger systems encounter different atmospheric conditions by extending over greater areas, and the possibility of trouble increases, also the amount of possible damage resulting from breakdowns. Thunder storms that may occur miles distant might be unknown at the station except for the snapping of the arresters or some sudden discharge.

The object should be to select the best method of protecting the system and then to apply a sufficient number of lightning arresters judiciously located in suitable positions on the system to prevent absolutely any disruptive discharges from entering the station and damaging the apparatus.

Special sets of arresters should be connected immediately outside of the station. On account of the extreme suddenness of the surges caused in the line by lightning discharges and other static disturbances, the gaps of the arrester, and ground connection also, must be able to discharge electricity very freely, in fact more rapidly than it appears on the line; otherwise, a dangerous rise of potential on the line will not be prevented.

INSTALLATION OF ARRESTERS

62. Before arresters are installed, the characteristics of the surrounding territory should be carefully studied, and if possible, statistics obtained regarding the frequency and severity of atmospheric electrical disturbances. The information obtained may be somewhat of a guide as to the amount of protection necessary.

63. Location of Arresters.—As regards the location of lightning arresters, electric systems may be divided into two groups:

1. Systems in which the individual pieces of apparatus, such as transformers, motors, arc lights, etc., are many in number and widely scattered. In these cases lightning arresters should be located at a number of points for the purpose of protecting the whole line; they should be more numerous on the parts of the line particularly exposed, and fewer in number on the parts that are naturally protected, especially those parts shielded by tall buildings or numerous trees. Special efforts should be made to protect the station by connecting sets of arresters on each line and causing the discharge to pass to ground before it enters the station. No definite statement can be made as to the number of arresters needed per mile, as the requirements will vary widely according to atmospheric disturbances in the locality.

2. Systems in which the apparatus is located at a few definite points, as on a high-tension transmission line. In such cases the arresters should, in general, be located to protect especially those points where apparatus is situated;

that is, should be placed with the object of protecting the apparatus rather than the line as a whole. Where circuits are part underground and part overhead, sets of arresters should be connected at the points of entrance to and exit from the underground system.

When determining the safest method of mounting and insulating the arresters, it should be estimated that all parts of the arrester except the grounded end of the series-resistance may be momentarily at line potential during the discharge; therefore, the necessity of extra insulation becomes self-evident.

Two high-tension arresters attached to different line wires should not be placed side by side without either a barrier or a considerable space between them. It is preferable to place them on different poles.

PROTECTION BY CONTINUOUS DISCHARGE

64. For overhead systems, excellent protection has been secured by the placing of barbed wires on the pole lines above the lines used for distribution; the barbed points serve to collect the electricity, and the barbed wires should be thoroughly grounded, at least as frequently as every three or four poles. An easy method of doing this is to put a copper plate under the base of the pole, having the ground-wire connection soldered on the plate and stapled along the surface from the base of the pole to the top, where it is connected to the barbed wire. The effect of this sort of protection is to discharge the atmospheric electricity silently and continuously, and this method under severe test has proved successful over large areas, with systems reaching from 30 to 50 miles or more from the station.

Fig. 58 shows the principle of the **Westinghouse tank arrester,** a type that has been much used on street-railway circuits where one side of the system is grounded. The arrester is connected to the series of choke coils S by closing plug switches K, K, K. The arrester consists of tanks T, T, T containing carbon electrodes c, c, c; the line is attached at L

and the other end of the choke coil goes to the dynamo or line bus-bar. A circulation of running water is maintained through the tanks and there is thus a continuous non-inductive path of high resistance to ground for any charges that may accumulate on the line. The water has such a high

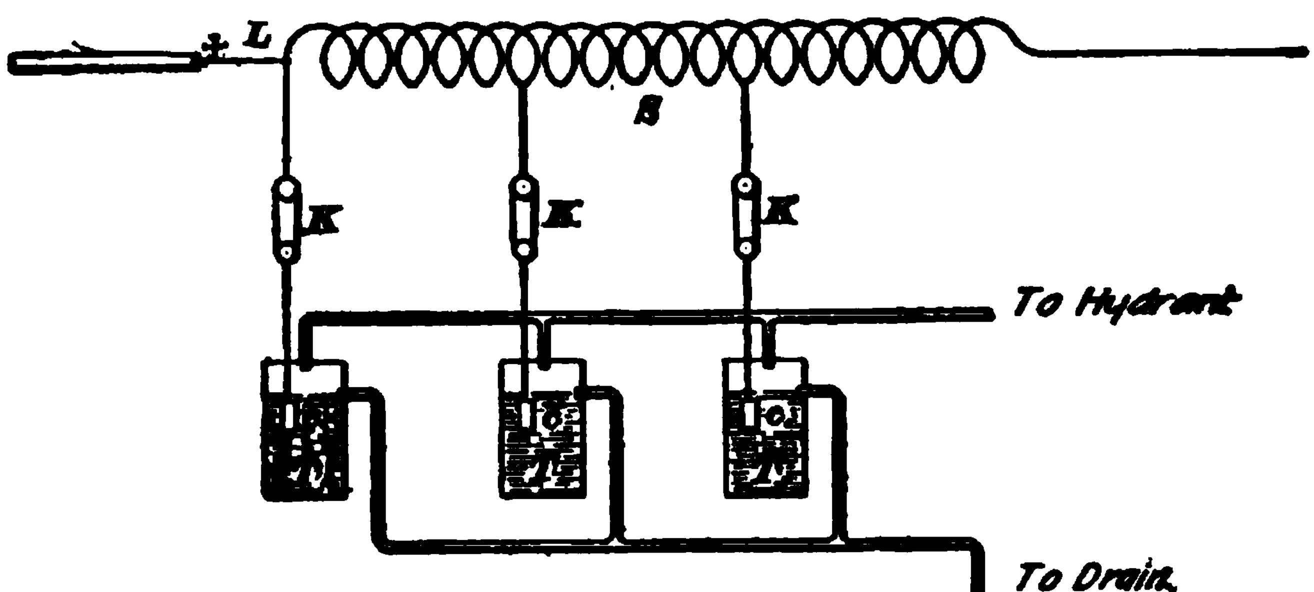


FIG. 58

resistance that the leakage of dynamo current to ground is not large. There is some leakage, however, and this type of arrester is only connected to the system during thunder storms, but while connected it affords very efficient protection.

PROTECTION FROM STATIC CHARGES

65. Static Effects on High-Tension Systems.—It has been found on systems where high pressure is used that under certain circumstances, parts of the system may be subjected to pressures very much higher than the normal. These effects, for want of a better name, are spoken of as being due to "static." They may be caused by any sudden change in the E. M. F. of the system, as, for example, when a dead circuit is suddenly connected to live bus-bars, when a transformer is switched on to a circuit, when a circuit is suddenly cut off from the bus-bars, etc. These effects are not due so much to the static charges themselves, but to the fact that when a device is switched on to a live circuit, a current wave at once tends to pass through the device, and if this wave meets with opposition, pressures much higher than the ordinary pressure of the system may be set up. This is somewhat analogous to the case where a current of

water is flowing rapidly through a pipe. There will be a certain pressure on the walls of the pipe due to the head of water, and this pressure will be practically constant. If, however, the flow of water be stopped by suddenly closing a valve in the pipe, the pressure will for an instant rise to a very high amount, producing the well-known water-hammer effect. These sudden rises in pressure on high-tension circuits may result in puncturing the insulation of transformer coils, armature coils, cable insulation, or other parts exposed to the high pressure. Take the case where a transformer is suddenly connected to a source of high E. M. F. The windings tend to become charged instantly, but owing to the self-induction of the coil the current wave that tends to enter is choked back and a pressure may be set up between the various layers of the winding that is very much higher than the normal, thus tending to cause a breakdown. To overcome these bad effects, a choke coil may be inserted in series with the device to be protected. This coil chokes back or flattens out the wave, and allows the pressure applied to the device to rise gradually. The choke coil must be heavily insulated, and large enough to flatten out the wave so that the latter will not injuriously affect the device to be protected. This means that the coil must be large, and it is difficult to insert a large choke coil in the circuit without causing a considerable waste of energy and drop in voltage. Another method of protection is to use a choke coil in combination with a spark gap that will break down whenever the pressure rises above a predetermined amount. This arrangement is practically the same as a lightning arrester, and a number of large plants have their lines fully equipped with lightning arresters even though the distributing lines are entirely underground and hence safe from lightning discharges. The lightning arresters are in such cases installed to protect the cables against abnormal pressures caused by the so-called static effects.

66. Static Interrupter.—In some cases, especially on high-tension lines operating at pressures higher than 16,000

or 18,000 volts, a device known as a **static interrupter** is installed to protect large transformers and other apparatus from the high pressures mentioned above. Fig. 59 shows the essential parts of the device as made by the Westinghouse Company; one line only is shown in the figure, but it is necessary, of course, to place one of the interrupters in each line. *A* is a choke coil and *B* the primary coil of a transformer or the winding of other apparatus to be protected; *C* is a condenser connected between *A* and *B*; the other terminal of *C* is connected to ground through a fuse *D*. If the primary coil *B* were suddenly switched on to a live line without the interposition of *A* or *C*, a very high potential would at once be developed at point *E*, because the current wave could not penetrate the layers of the winding instantly. The coil *A* retards the wave, and furthermore the condenser *C*, having a large capacity compared with the coil *B*, takes up a considerable portion of the charge, thus reducing the potential of *E* for the time being and allowing the charge to progress well through the coil before the pressure at *E* rises to the full amount. In other words, the condenser *C* acts in much the same manner as an air chamber used on a water pipe to prevent the shock due to a water hammer. By using the condenser in conjunction with the choke coil, a much smaller coil is sufficient than if the coil were used alone, and it can thus be designed so that it will not insert an objectionable amount of resistance or inductance in the circuit. In practice, the coil *A* and condenser *C* are mounted together in a case filled with oil, so that the interrupter has about the same appearance as an ordinary oil-insulated transformer. The interrupters are connected directly to the apparatus to be protected so as to practically form part of the apparatus, because they must be so situated

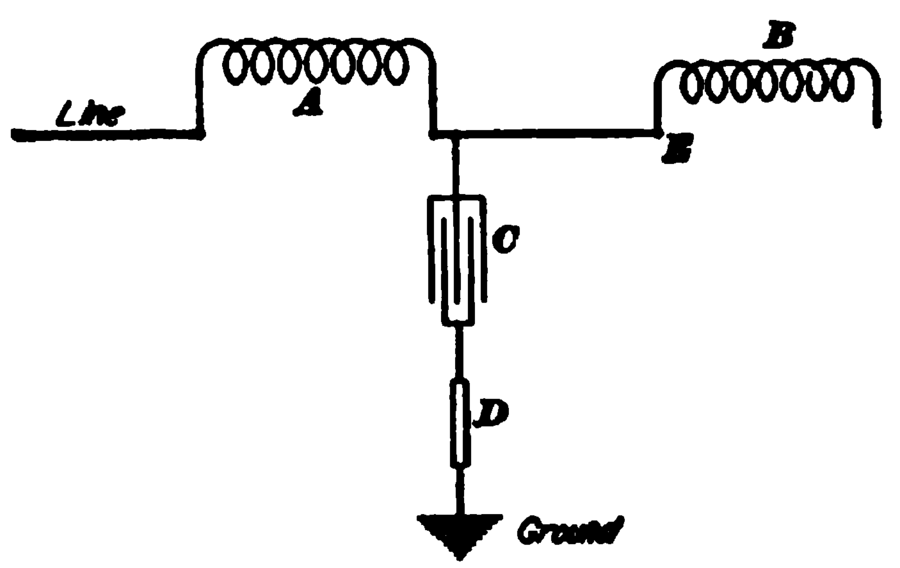


FIG. 59

that they will come between the device to be protected and the source of static disturbance, as, for example, a high-tension switch.

Overhead systems will naturally be equipped with lightning arresters and these will serve to a considerable extent as protection against static discharges. Underground systems carrying current at high potential are liable to accumulation of static charges that may cause a rupture of the cable insulation. Assuming that alternating current of high potential is transmitted through an underground system, it will be found that there is a static charge developed in the cable covering or, under some conditions, in the conduit ducts. Certain types of conduit have been found to develop condenser capacity under these conditions. A 6-foot section of 3-inch, creosoted, pump-log conduit was tested for capacity with an insulated wire drawn through it and connected in circuit with a high-potential current. In the darkness, a faint blue light could be distinguished on the interior surface of the duct. When circuits are quickly opened, the cable tends to set up violent oscillations of the system, and the resultant static potential is liable to rupture, at its weakest point, the insulation of the cable. Static charges are also liable to accumulate on generators and switchboard apparatus. Electrostatic ground detectors should be used to show the appearance of any static charge on the line, and on which particular conductor it may be located.

FIELD RHEOSTATS

67. Field rheostats are inserted in the field circuits of the generators in order that the voltage may be adjusted by varying the field strength. The rheostat must therefore be able to carry the field current continuously without overheating. The resistance of the rheostat will depend on the resistance of the field winding with which it is used, and the range of voltage variation desired. Very often the rheostat has a maximum resistance about equal to that of the field, though in many cases it is not necessary to have as much as

this. Field rheostats are made in a great variety of styles and sizes suited to various classes of machines. They are also constructed for various methods of mounting, but all consist of a suitable resistance connected to a multipoint switch of some kind so that the amount of resistance in the field circuit can be varied. Small or medium-sized rheostats are generally mounted on the rear of the switchboard and operated from the front by a hand wheel. For large rheostats the resistance can be separate from the board with leads

FIG. 60

running to the switch located on the back of the board, or the switch can be mounted with the resistance and be operated from the switchboard by means of chain and sprocket wheels, or from a pedestal, with a hand wheel, placed in front of the board. Either of the latter methods are preferable to running leads from the resistance to the board, because quite a number of wires are required and there is danger of some becoming broken. In very large stations, the rheostats are

often bulky and must be placed quite a distance from the switchboard; in such cases the rheostat switch is moved by means of a small motor controlled from the switchboard.

68. Fig. 60 shows a **General Electric field rheostat** of a type much used for 500-volt railway switchboards. The rheostat is mounted on the back of the board and operated by the hand wheel *W* in front. The resistance wire or strip is wound on asbestos tubes that are afterwards flattened and clamped between pieces of sheet iron covered with asbestos, the iron strips serving to conduct the heat from the wire. In rheostats of large capacity, the resistance is in the form of cast grids. Fig. 61 shows the connections for the rheostat, Fig. 60. A small resistance *c* is connected to the contact rings *b*, *b* and contacts *a*, *a'*. When the arm is in a position where *a*, *a'* are on adjacent contact points, resistance *c*, which is equal in amount to the resistance between the rheostat contacts, is in parallel with the resistance between the contacts. Thus, by using resistance *c*, the change in resistance due to a movement of the arm from contact to contact is one-half what it would be if no auxiliary resistance were used. The variations in field strength are, therefore, as gradual as in an ordinary rheostat using twice the number of contacts.

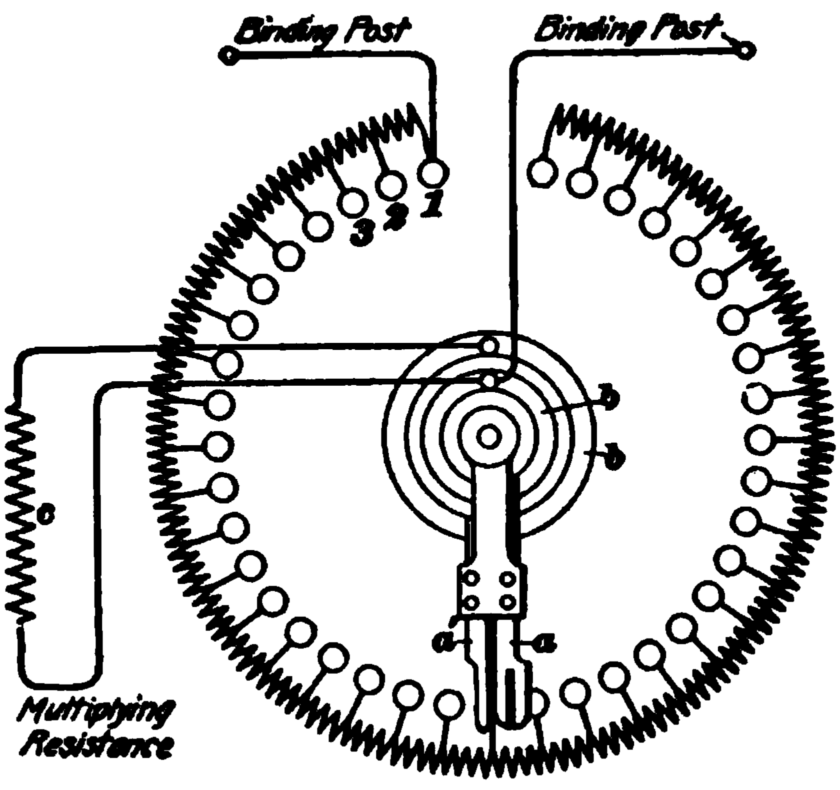


FIG. 61

69. Field Switches.—Field switches are used to open the field circuits of dynamos and they are, therefore, of comparatively small current-carrying capacity. Field windings, particularly those of large alternators or high-voltage, direct-current machines, have a high inductance, and if the circuit is suddenly opened very high E. M. F.'s may be induced,

sufficient in many cases to break down the field insulation. It is therefore necessary, with such machines, to arrange the field switch so that when the field circuit is broken, a path is at the same time established through a discharge resistance. This allows the induced E. M. F. to set up a current through the local circuit thus provided, and strain on the windings is avoided. Fig. 62 shows a common arrangement of field switch and discharge resistance as used for 500-volt street-railway generators. The tongue t is wide enough to bridge over the gap between the contact segments a, a' of the switch S, which is shown in the position that it occupies when the generator is in operation. The current then passes through the field rheostat r and the switch S, as indicated by the arrowheads. When the switch is moved to the position indicated by the dotted line, connection between the field and the negative side of the armature is broken, but before the break takes place, tongue t comes into contact with a', so that the shunt field, the rheostat r, discharge resistance r', and pilot lamp l all form a closed circuit. The shunt field is thus able to discharge through this closed circuit. When the machine is being started, the tongue t is placed in its mid-position, so that current can flow through r' and l as well as through the shunt field and rheostat r. As the machine builds up, the pilot lamp becomes brighter, thus giving the attendant an indication as to whether the machine is "picking up" properly or not. After the machine has come up to voltage, the switch is moved to the position shown in the figure and the pilot lamp is cut out. On some boards, five or six lamps in series are used in place of the resistance r' and the single lamp l. Another type of field

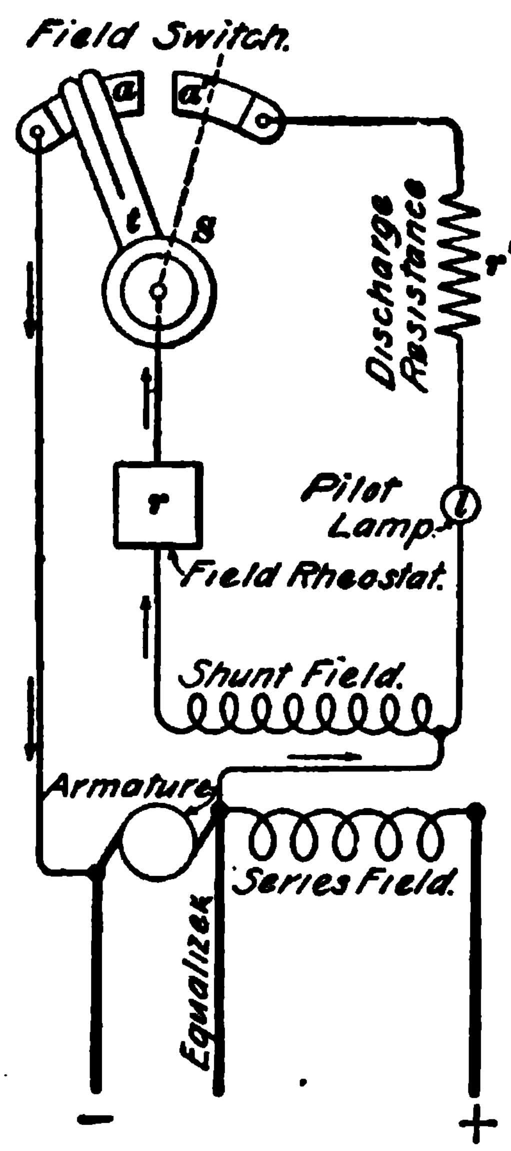


FIG. 62

switch with field-discharge resistance, as used in the exciting circuit of alternators, is shown in Fig. 73.

70. Recording Wattmeters.—Well-equipped switchboards are generally provided with one or more **recording wattmeters**, to record the output, in kilowatt-hours, of each machine or of the station as a whole. Readings of the total output are very valuable in making tests on the efficiency of the station and in keeping track of the cost per

FIG. 63

kilowatt-hour. Sometimes it may be desirable to know the output of individual machines, but usually a knowledge of the total output is sufficient and a single total output recording meter is installed, as shown at *11*, Fig. 65.

Fig. 63 shows a **Thomson recording wattmeter** for use on direct-current switchboards. These meters have to carry large currents, hence their construction differs somewhat from the ordinary Thomson meter, though the principle

of operation is the same. The series-coils of the ordinary meter are here replaced by the heavy copper bar *a*, through which the current passes, connection being made on the back of the board to the lugs *b*, *b*. Above and below this bar are the two small armatures *c*, *c*, which are connected, in series with a resistance, across the line, so that the current in them is proportional to the voltage. Current is led into the armatures through a small silver commutator *d*, as in the ordinary recording meter, and the reading is registered on a dial *e* in the usual way. The damping magnets used to control the speed are contained in the case *f*. The main current flowing through the crosspiece *a* sets up a field around the crosspiece, and this field acts on the two armatures *c*, *c*. This instrument is constructed so that outside magnetic fields have little or no influence on it. In some of the older styles of meters, the magnetic field surrounding the heavy conductors on the back of the board affected the meter. In this meter any stray field affects both the armatures *c*, *c*, which are so connected that an outside field tends to turn them in opposite directions, and the disturbing effect is thus neutralized. The field set up by the instrument itself is in opposite directions on the upper and lower sides of *a*, so that these two fields propel the armatures in the same direction. For alternating-current boards, total-output recording meters of the induction type are used.

SWITCHBOARDS

71. The **switchboard** is a necessary part of every plant. Its object is to group together at some convenient and accessible point the apparatus for controlling and distributing the current, and the safety devices for properly protecting the lines and machines. Scarcely any two switchboards are alike in every particular; their layout and the type of apparatus used on them depend on the character of the system used, the number and size of dynamos, the number of circuits supplied, etc.

72. General Construction.—Switchboards were formerly made of wood and consisted simply of a built-up board or wall sufficiently large to accommodate the instruments. This construction was objectionable on account of the fire risk, and the only type of wooden board now allowed by the Fire Underwriters consists of a skeleton frame of well-seasoned hardwood filled and varnished to prevent absorption of moisture. A skeleton board of this kind is cheap and is suitable for those places where the expense of a slate or marble board is not warranted. Modern boards are nearly always made of slate, marble, soapstone, or brick tile. Slate is usually satisfactory for low-tension work, but it should be avoided on high-tension boards, because it is liable to contain metallic veins. A good quality of marble is the material generally used for modern boards. The slabs making the boards may vary from $\frac{3}{4}$ inch to 2 or $2\frac{1}{2}$ inches in thickness, depending on their size. Most central-station slate or marble boards are made 2 inches thick with a bevel around the edge of $\frac{1}{4}$ or $\frac{3}{8}$ inch. They are supported by bolting to angle irons *i*, *i*, Fig. 64, and are stood out from the wall by means of braces *b*, *b*. Station boards built up as shown in Fig. 64 are usually about 90 inches high. It has become customary to build up boards in panels, each panel carrying

the apparatus necessary for a generator or one or more feeders. Those carrying the instruments for the generators are known as **generator panels**; those carrying the instruments for the feeders, as **feeder panels.** This system allows the board to be easily extended as the plant grows in size, as panels can be added to those already in use. The extra panels are attached as indicated by the dotted lines in

FIG. 64

Fig. 64, the panels being held together by means of bolts passing through holes *h* in the angle irons. For high-pressure boards using over 3,000 volts, the marble should be polished on both sides in order to secure better insulation. Also, if oil switches are mounted on the back of the board, the marble should be coated with varnish or similar substance to prevent absorption of oil.

DIRECT-CURRENT SWITCHBOARDS

73. Railway Switchboard.—Fig. 65 shows a typical **direct-current switchboard** as arranged for street-railway operation on the ordinary 500-volt rail-return system. The board consists of three generator panels *A*, *A*, *A*, one total-

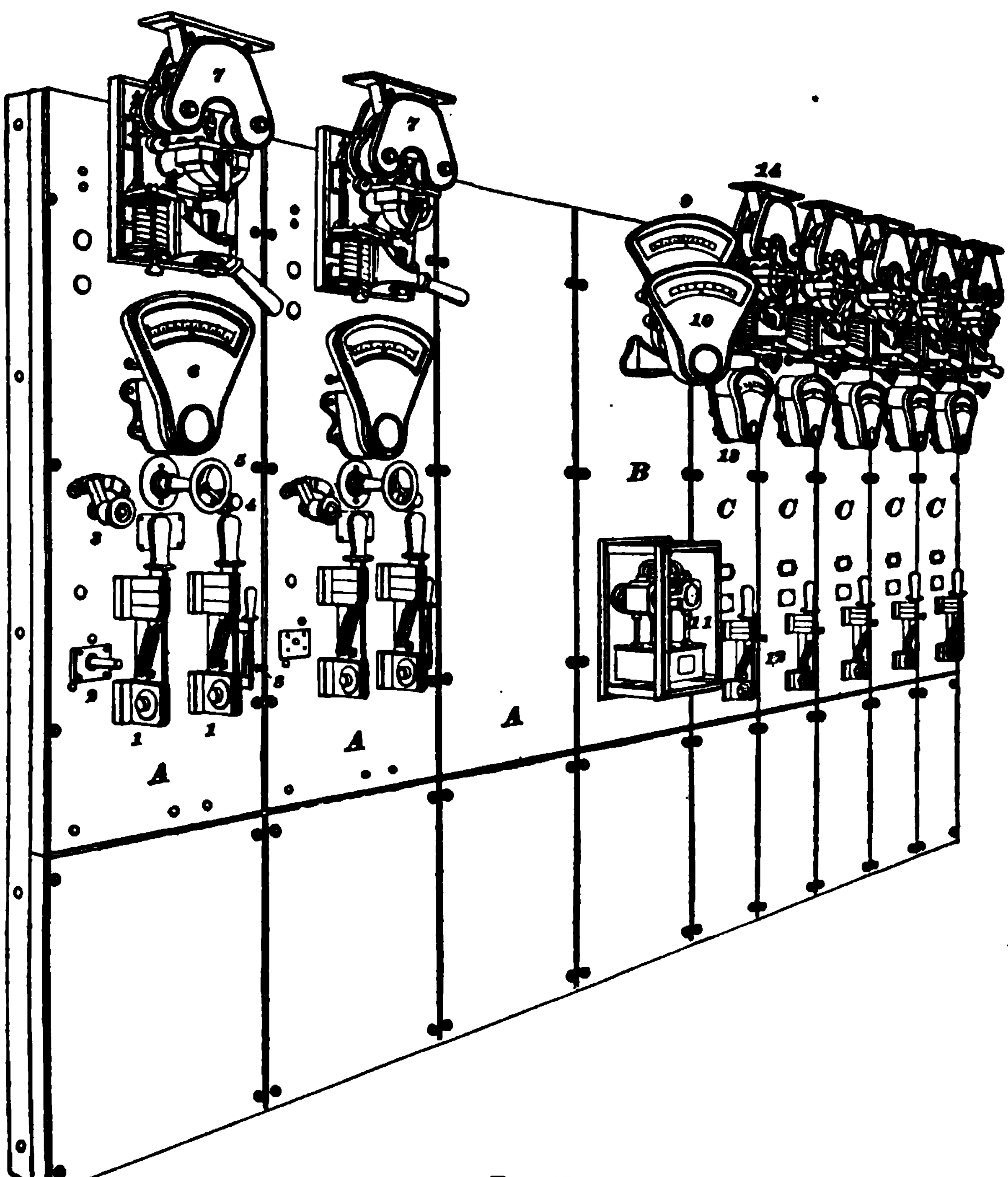


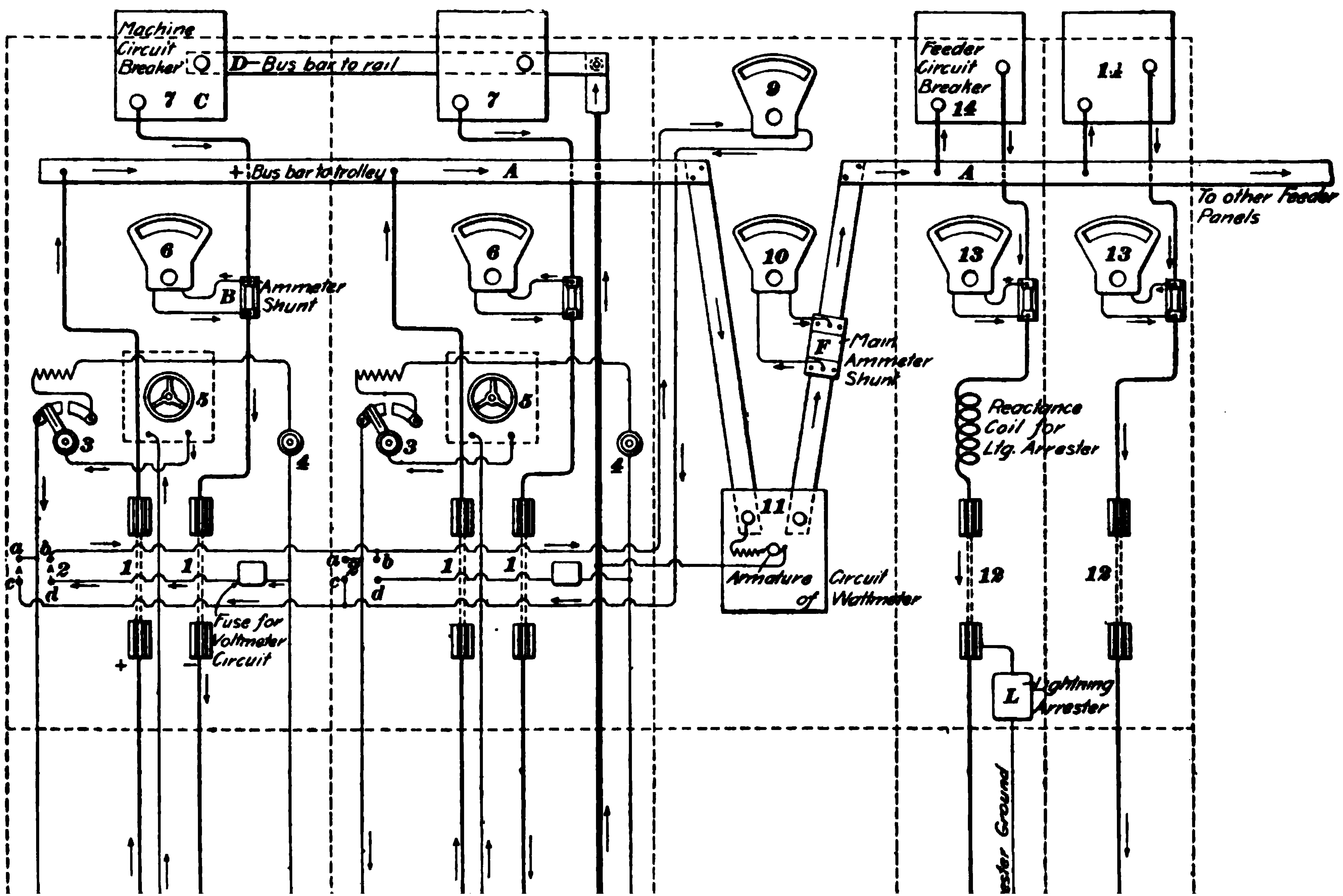
FIG. 65

output panel *B*, and five feeder panels *C*, *C*, etc. One of the generator panels is left blank to provide for a future generator. Each generator panel is equipped with + and − main switches *1*, *1*, voltmeter plug *2*, field switch *3*, pilot-lamp

receptacle *4*, field rheostat (operated by handle *5*), machine ammeter *6*, and machine circuit-breaker *7*. The total-output panel carries a voltmeter *9* that can be connected to either machine by means of the voltmeter plug, a total-output ammeter *10* that indicates the combined current output of the generators; recording wattmeter *11* records the total output in kilowatt-hours. Each feeder panel is equipped with a single-pole feeder switch *12*, a feeder ammeter *13*, and a feeder circuit-breaker *14*. Since on a ground-return railway system the current returns through the rails, which are connected to the negative bus-bar, the feeders are connected to the positive bus-bar only, hence single-pole feeder switches are used.

Fig. 66 shows the connections for the board. Two feeder panels only are shown and the instruments and switches are numbered to correspond with Fig. 65. If lightning-arrester reactance coils are used on the switchboard, they will be inserted as indicated on the left-hand feeder panel. The equalizer switches are mounted on pedestals near the generators and the equalizer connections are not brought to the switchboard. When the voltmeter plug is inserted in either receptacle, terminals *a* and *c*, *b* and *d* are connected, thus placing the voltmeter across either machine; the voltmeter connections are made at the lower terminals of the main switch, or "back" of the switch, so that voltmeter readings can be taken before a machine is thrown in parallel by closing the switch.

74. Lighting or Power Switchboard.—Fig. 67 shows connections for a simple two-wire board suitable for two generators and three two-wire feeders. Three bus-bars are provided, the equalizer bar being mounted on the board. Each generator panel has a machine ammeter *a* connected across ammeter shunt *s*, circuit-breaker *b*, voltmeter plug *c*, main switches *d*, field rheostat *e*, and pilot lamps *h*, *h*. As this board is intended for low pressure, 110 to 250 volts, field switches and field-discharge resistances are not provided. A total-output ammeter *M* is connected between the


Machine Circuit Breaker
7 C
D—Bus bar to rail
7
+ Bus bar to trolley
A
6
B
Ammeter Shunt
6
5
3
4
5
3
4
a
b
2
c
d
1
1
a
b
c
d
1
1
Fuse for Voltmeter Circuit
+
−
9
10
F
Main Ammeter Shunt
11
Armature of Circuit Wattmeter
Feeder Circuit Breaker 14
14
A
To other Feeder Panels
13
13
Reactance Coil for Ltg. Arrester
12
12
L
Lightning Arrester

45B

FIG. 66

§ 25

FIG. 67

generator and feeder panels to indicate the combined current output of the generators; voltmeter *V* indicates the voltage of either machine. Each feeder panel is equipped with a feeder circuit-breaker *g* and feeder switch *f*. The lamps *k*, *l* may be connected either across the bus-bars, as shown for *l*, or to the feeders, as at *k*. In the latter case the lamp will go out when the circuit-breaker of the corresponding feeder trips, and the lamp thus serves as a circuit-breaker telltale. If a lamp ground detector were used on the board, it would be connected as shown by the dotted outline at *D*.

In large stations there are, of course, a large number of generator and feeder panels on the switchboard. This increases the size of the board, but each generator or feeder added merely repeats the connections of the other panels and no new features are involved.

ALTERNATING-CURRENT SWITCHBOARDS

75. The arrangement of ordinary **alternating-current boards** is, in many respects, similar to that of direct-current boards. They are usually built up in panels in the same way as the boards previously described. Owing to the fact that alternators are generally separately excited, the switchboard contains some extra apparatus connected with the exciter that is not found on direct-current boards. The wiring and connections will also depend on whether single-phase or polyphase alternators are used.

76. Single-Phase Generator Panel.—Fig. 68 (*a*) and (*b*) gives front and rear views of a typical alternating-current panel for one single-phase generator. Such a board would be used where only one single-phase machine is operated on a single line, and represents about the simplest possible arrangement. This panel is equipped as follows: Main switch *a*, electrostatic ground detector *b*, voltmeter *c*, ammeter *d*, voltmeter switch *e*, field switch *f*, generator rheostat *g*, exciter rheostat *h*, main fuses *k*, and potential transformer *t*. The main switch *a* is of the quick-break type and is provided with the marble barrier *l* between the blades to prevent arcing

across. The switch f is used to disconnect the field of the alternator from the exciter and is provided with auxiliary carbon contacts to prevent burning at the blades. The rheostat g is mounted on the back of the board and is operated by a hand wheel in front. This rheostat is connected in series with the field of the alternator, so that the field current may

(a) (b)

FIG. [illegible]

be adjusted. The rheostat h is in the shunt field of the exciter and serves to regulate the exciter voltage. Sometimes the rheostat g is not used, the field current of the alternator being increased or decreased by raising or lowering the exciter voltage by means of the rheostat h. It is best, however, to have the rheostat g also, especially if two or more alternators are

excited by the same exciter, because it then allows the field current of each alternator to be adjusted independently of the others. The voltmeter *c* is connected to the machine through the potential transformer *t*, and a small voltmeter switch *e*

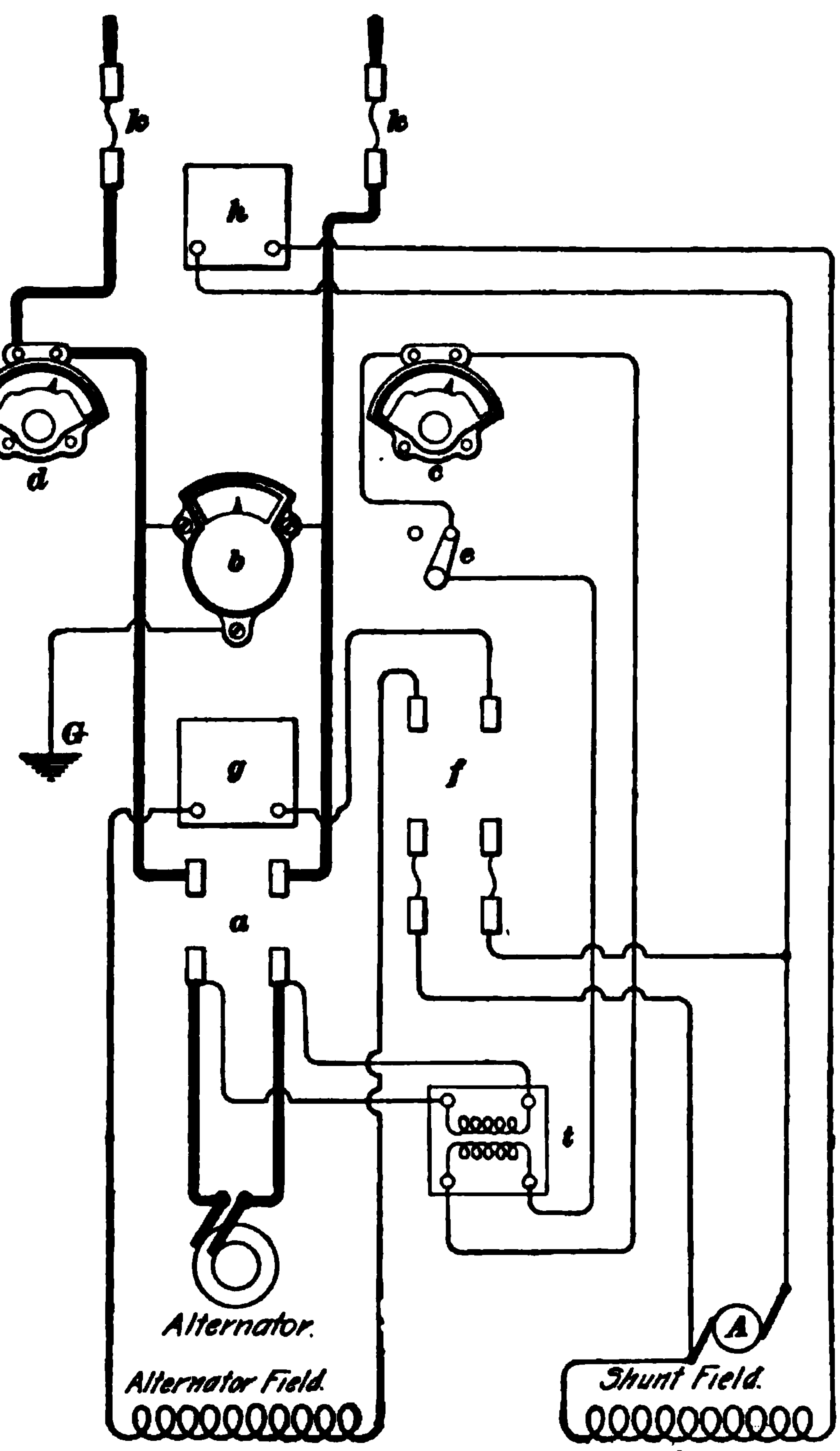


FIG. 69

is somtimes placed in circuit so that the instrument may be cut out of circuit when not needed. The main fuses *k* are of the enclosed type. No synchronizing device is needed on this board, as it is intended for a single machine only.

77. The rear view of the board will give a good idea as to the way in which the wiring is arranged. Heavy rubber-covered wire should be used for this work, and especial care should be taken to see that everything is thoroughly insulated and neatly done. The leads from the alternator connect to terminals *1* and *2*, and the line connects to terminals *3* and *4*. The potential transformer t used to lower the pressure for the voltmeter, is mounted on an iron framework at the base of the board, and when the lightning arresters are placed on the board, they are usually mounted on a similar framework rather than on the back of the board itself. This makes them stand out so that they do not crowd the wiring on the back. Fig. 69 shows the general scheme of connections on a board similar to that shown in Fig. 68.

78. Switchboards for Parallel Running.—When alternators are operated in parallel, it is necessary to provide bus-bars and have the different machines arranged so that they may feed into them. Fig. 70 shows connections for two three-phase machines arranged for parallel running, as used by the Westinghouse Company. Main fuses are here provided between the alternator and main switch, and these may or may not be placed on the switchboard itself. The field excitation is carried out in the same way described in connection with Figs. 68 and 69, about the only difference being that field plugs c, c' are used instead of field switches. Three ammeters are provided for each generator, one in each leg of the three-phase system. In many cases, however, two ammeters only are used, as shown on the feeder circuit. T and T' are the potential transformers that furnish current to the voltmeters V, V' and also to the synchronizing lamps l, l'. The voltmeter is also made to serve as a ground detector by using the plug switches R, R' and ground keys k, k'. The synchronizing lamps are connected to the transformers by inserting plugs p, p'.

79. Usually when a number of alternators are operated in parallel, it is advisable to have their exciters arranged so that they may be operated in parallel also. If

one exciter breaks down, the others may then supply the alternator that would ordinarily be supplied by the disabled

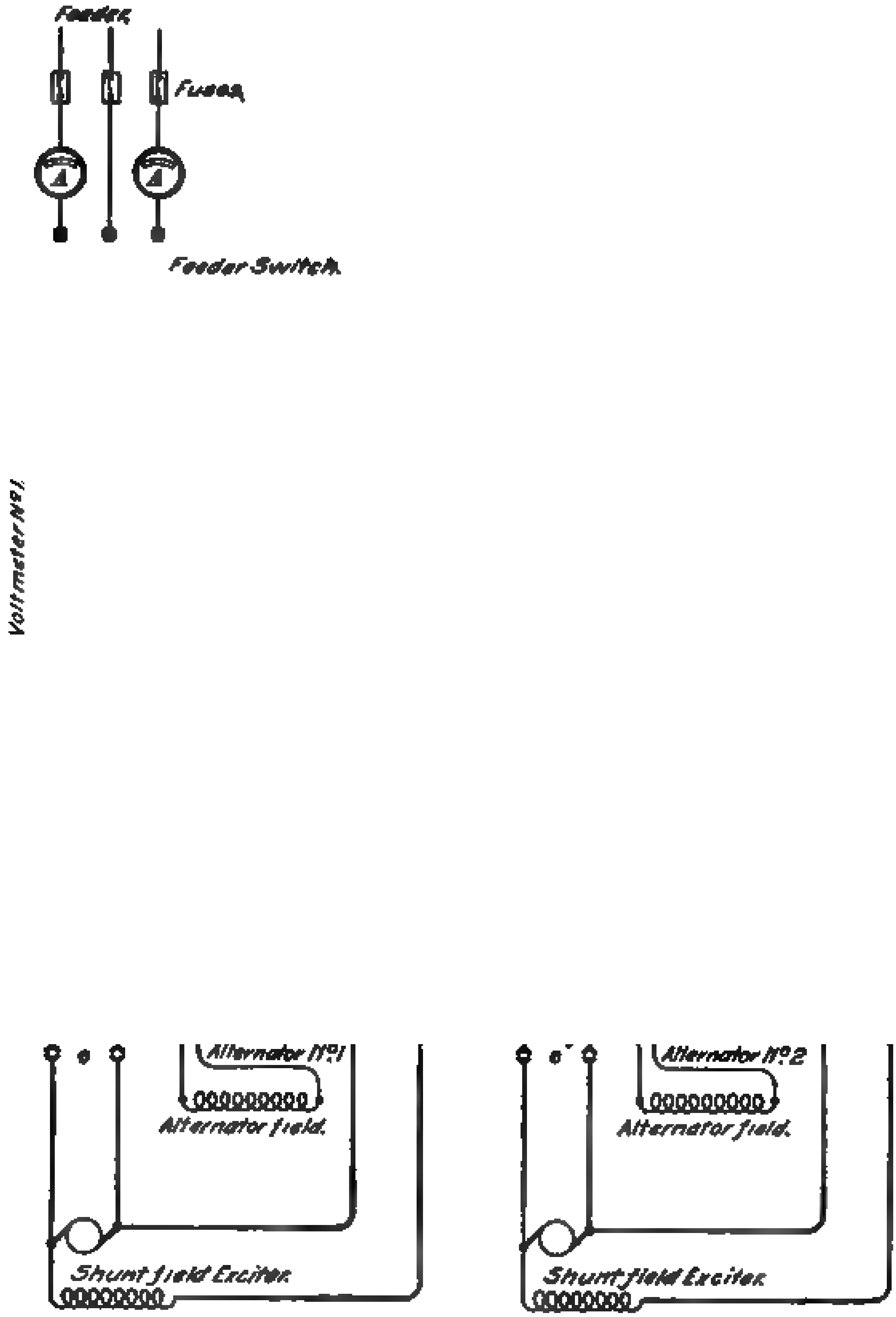


FIG. 70

machine. Again, in large plants, it is quite customary to supply all the alternators with their field current from one

or two large exciters that feed into a pair of exciter bus-bars, from which the several alternators are supplied.

80. General Arrangement of High-Pressure Switchboards.—In low-pressure work, the switchboard consists of a group of slate or marble panels on which the switches, bus-bars, instruments, and all devices necessary for the control of the station output are placed. Such crowding of the parts is dangerous on a high-pressure board, and the tendency in large stations is to separate the high-pressure switches and bus-bars so that a short circuit on one part will not spread to others and result in a serious interruption of the service. The switchboard panels in this case carry only the instruments and small switches necessary for controlling the main switches that are usually operated either by compressed air, electric motors, or electromagnets. No parts carrying high pressure are exposed on the surface of the board, thus insuring safety to the attendant; a switchboard arranged on this plan occupies a large amount of space. Fig. 71 shows a cross-section of the switchboard in the Waterside station of the New York Edison Company. This board controls the output of 16 generators, each having a capacity of 4,500 kilowatts at 6,600 volts. The board is a good example of a number that have been installed in modern stations delivering a large output at high pressure, and brings out the method of separating the various parts. The main cables from the generator first pass through the generator oil switch A, and from there they lead to the two selector oil switches B. The object of these switches is to allow the generator to be connected to either of the sets of bus-bars C, D. There are, therefore, two oil switches in series between any generator and the bus-bars into which it is feeding, so that if one switch fails to operate at any time, the generator can be cut off by means of the other. From the bus-bars, the current passes to a non-automatic oil switch E, and then through an automatic oil switch F, from whence it passes out on the feeder G. E' and F' are a similar pair of switches for another feeder. H, H' are knife-blade switches that allow

Fig. 71

any feeder to be connected to either pair of bus-bars. These switches are never opened while the current is on; other knife-blade switches *K*, *K'* allow switches *B* to be disconnected from the bus-bars. The potential transformers used for supplying current to the voltmeter, wattmeters, or other instruments are shown at *L*, and the current transformers are shown at *M*. It will be noted that all the transformers, bus-bars, knife switches, and working parts of the oil switches are separated from each other by brick partitions, and the various parts are so widely separated that there is little danger of fire communicating from one to the other.

The instruments connected with the control of the feeders are mounted in the upper gallery at *N*, there being a panel for each feeder. On these panels are mounted the feeder ammeters, indicating wattmeter, power factor indicator, pilot switches for controlling the feeder oil switches, and all other devices connected with the control and measurement of the outgoing current.

81. The apparatus for the control of each generator is mounted on a pedestal at *O*, there being a pedestal for each generator. This pedestal has mounted on it the rheostat dial switch for adjusting the field excitation of the alternator, the resistance controlled by this switch being mounted at *P* in the gallery below. In addition to this, each pedestal is provided with a field switch for cutting off the exciting current, a switch for controlling the engine speed when synchronizing, synchronizing plug, and pilot switches for controlling the main generator switches *A* and the selector switches *B*. The ammeters, voltmeters, and other instruments connected with the generators are mounted at *R* on a small panel immediately above the generator pedestal. By mounting the generator controlling apparatus on separate pedestals instead of side by side on panels, the connections are kept separated to better advantage, and the devices are also separated, so that there is less danger of throwing the wrong switches.

The current for exciting the fields of the generators is

supplied from motor-generator sets *S*, each consisting of an alternating-current motor coupled to a direct-current generator. The apparatus for starting and controlling each of these sets is mounted on a pedestal *T*, and the instruments connected therewith are mounted on panels *u* directly above the pedestal. *V* is a low-pressure, direct-current switchboard from which the exciter current is supplied.

From the above it will be seen that a high-pressure switchboard for a large station involves a wide variety of apparatus and occupies a large amount of space. The switchboard used in the large station of the Manhattan Elevated Railway, New York, is similar in its general design and handles current at 11,000 volts. In this station the operating board is equipped with small strips of brass that represent the main bus-bars, and the handles of the switches are so arranged that when moved, they apparently close or open the diagrammatic circuit on the controlling board. Signal lamps are also arranged to show whether a switch is on or off, the whole object being to arrange the controlling board so that the attendant will see just what connections exist between generators and bus-bars, and also what the result will be if certain switches are operated. The object in arranging the controlling board in this diagrammatic fashion is to lessen the danger of confusion when connections have to be rapidly changed—a feature of special importance where large generating units are involved.

82. Fig. 72 shows a switchboard installation for a high-tension station of comparatively small output. This view shows the arrangement of one of the feeder panels. The lever *l*, for operating the feeder switch, is placed on the panel *p* that rests on the floor of the lower switchboard gallery. The levers operate the oil switches *A*, *A* by means of the rods and bell-crank levers, shown in the figure. One of these rods *b* is of wood, so that the operating handle is effectually insulated from the switch. The bus-bars *B* are provided in duplicate and consist of copper rods well insulated with oiled tape. They pass through hard-rubber insulators that are supported by fiber pieces attached to the

angle-iron framework. Each feeder is provided with a current transformer *t*, none of the indicating instruments being connected directly to the high-tension lines. Each feeder is also provided with high-tension enclosed fuses *C*.

83. Fig. 73 shows the general scheme of connections for two of the generators and one of the feeders. This layout may be taken as an example where the generator supplies current at high pressure to the lines without the intervention

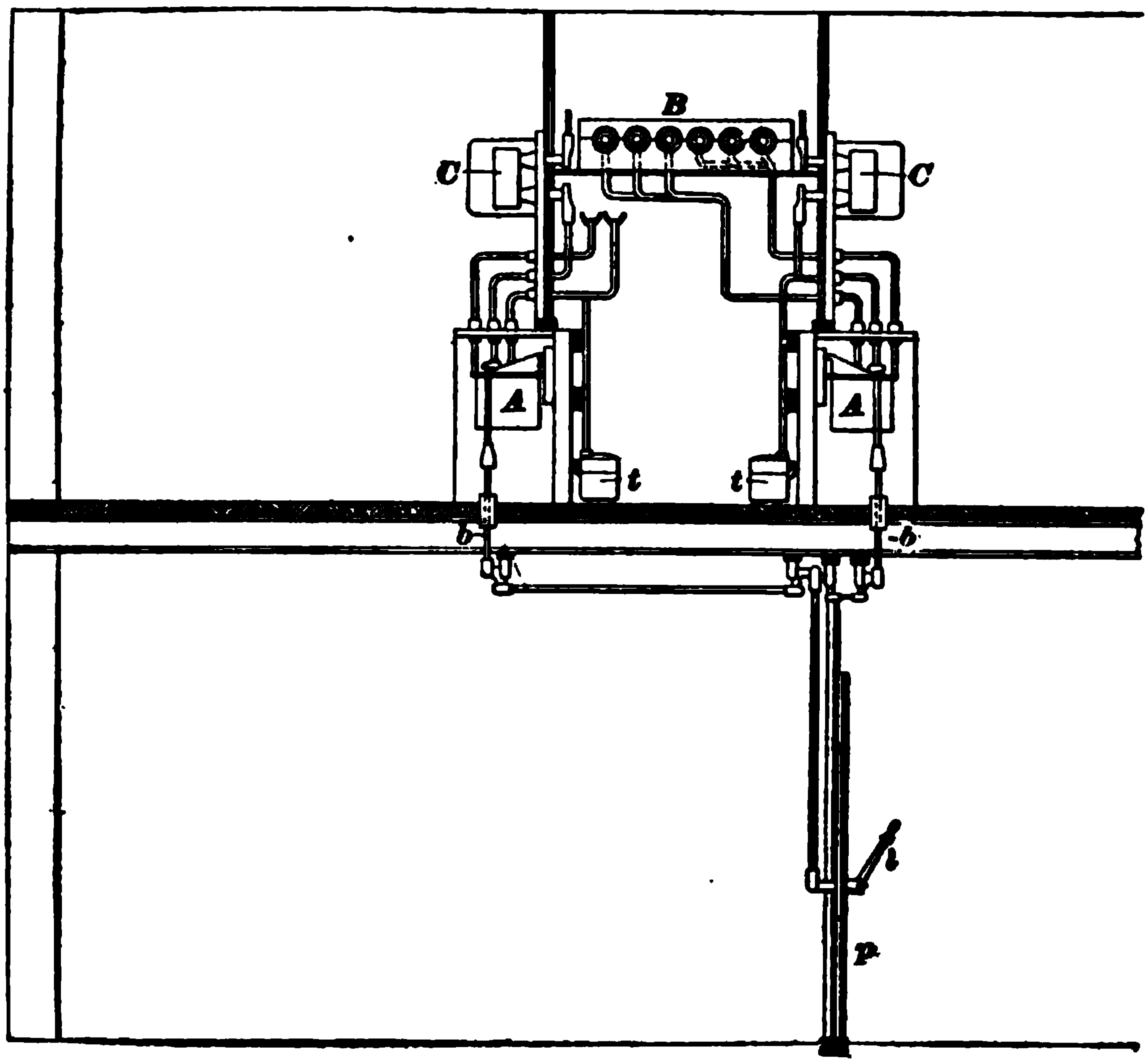
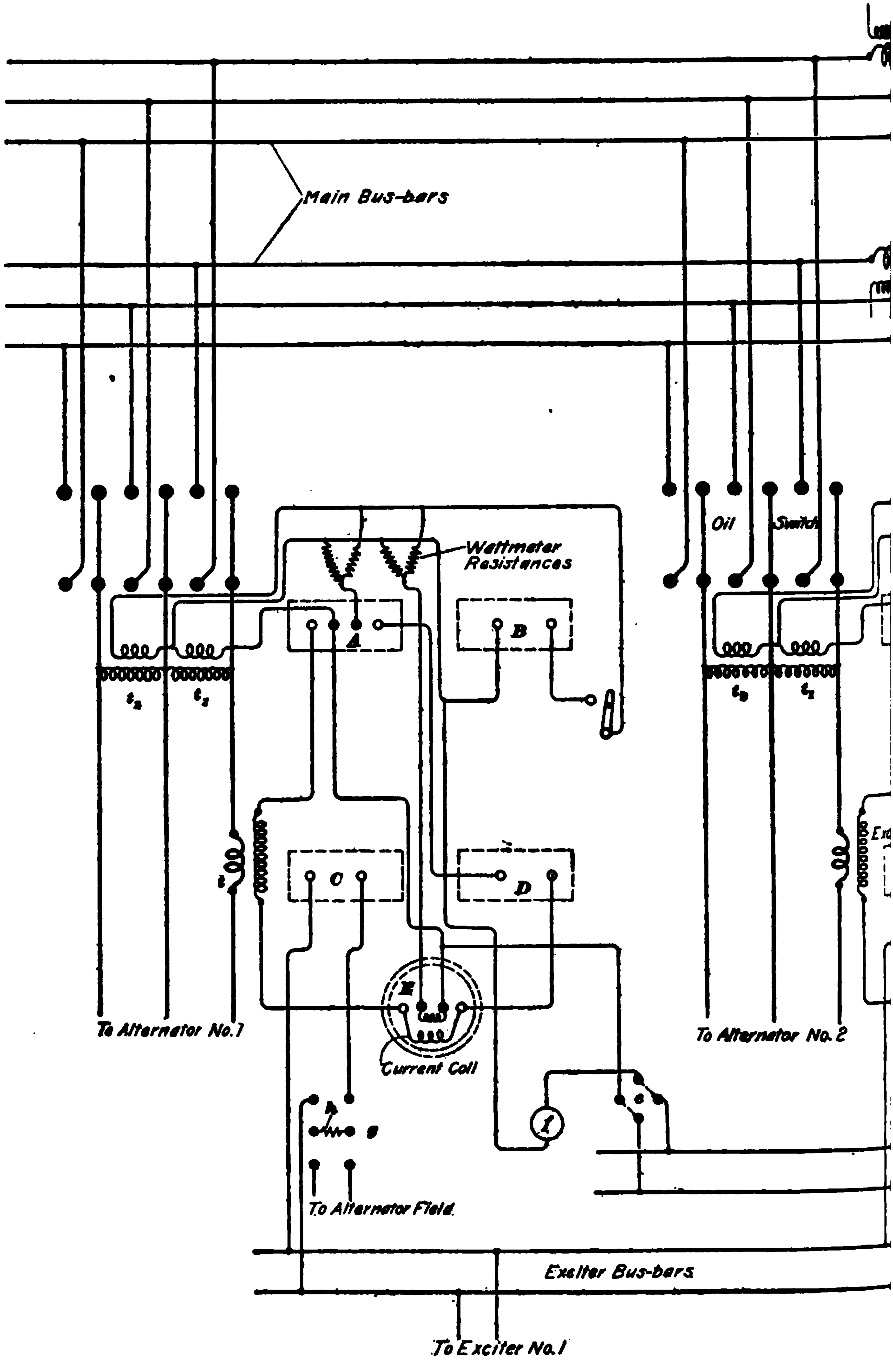


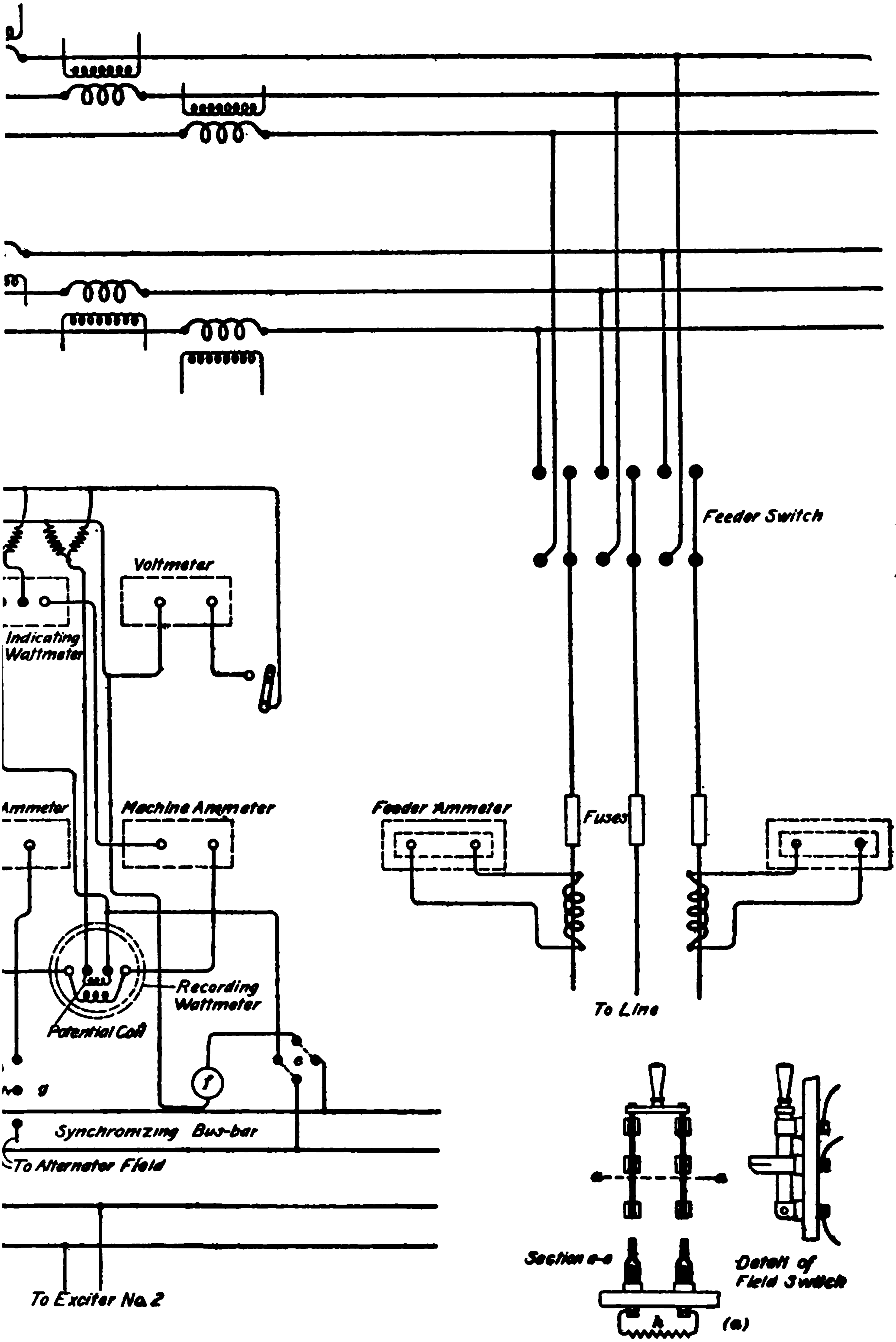
FIG. 72

of step-up transformers. Each generator is provided with an ammeter *D*, supplied from a current transformer *t*, and a voltmeter supplied from a potential transformer t_1. A second ammeter *C* is also connected in the field exciting circuit, so that the field current may be read at all times. The current transformer supplies the current coils of the indicating wattmeter *A* and the recording wattmeter *E*. *A* indicates the watts delivered by the alternator, and *E*

records the watt-hours or kilowatt-hours. The indicating wattmeter indicates the load on each machine, so that the attendant can see at a glance whether or not each machine is taking its share of the load and can adjust the governor on the engine or waterwheel accordingly. The switch *g* is for connecting the alternator field to the exciter bus-bars, and it is provided with two long clips between which a resistance *h* is connected, so that when the switch is opened this resistance is connected across the field terminals, thus taking up the discharge from the field and avoiding the danger of puncturing the field insulation. The construction of this switch is indicated in the small detail sketch (*a*). The long clips are formed so that when the switch is completely closed, the blades connect the lower and upper clips, but do not make contact with the middle clips. The synchronizing plugs are shown at *e*, *e*; and *f*, *f* are the synchronizing lamps. Each feeder running out from the station is provided with an oil switch, fuses, and two feeder ammeters. Sometimes three ammeters are used on the outgoing lines, as an ammeter on each line is often of service in indicating the condition of the line and also in showing whether the load is balanced or not. In some cases the fuses are replaced by automatic circuit-breakers, while in others the switch is provided with an automatic tripping device, so that the switch will open the circuit in case there is an overload or short circuit on the line. Current transformers *K* are connected in the bus-bars between the alternators and the feeders in order to supply total output ammeters.

84. Example of Double-Current Generator Installation.—Fig. 74 shows a simplified diagram of connections for two double-current generators feeding into a three-wire, direct-current system for supplying near-by points and furnishing alternating current, through step-up transformers, to high-tension feeders running to outlying points. All auxiliary apparatus, such as ammeters, voltmeters, etc., is omitted in order to bring out the main connections more prominently. The method of operation shown in Fig. 74 is used by the


Main Bus-bars
Wattmeter Resistances
Oil
Switch
A
B
t₂
t₁
C
D
E
Current Coil
h
g
f
e
To Alternator No. 1
To Alternator No. 2
To Alternator Field
Exciter Bus-bars
To Exciter No. 1



Feeder Switch
Voltmeter
Indicating Wattmeter
Ammeter
Machine Ammeter
Feeder Ammeter
Fuses
Recording Wattmeter
Potential Coil
To Line
Synchronizing Bus-bar
To Alternator Field
To Exciter No. 2
Section a-a
Detail of Field Switch
(a)

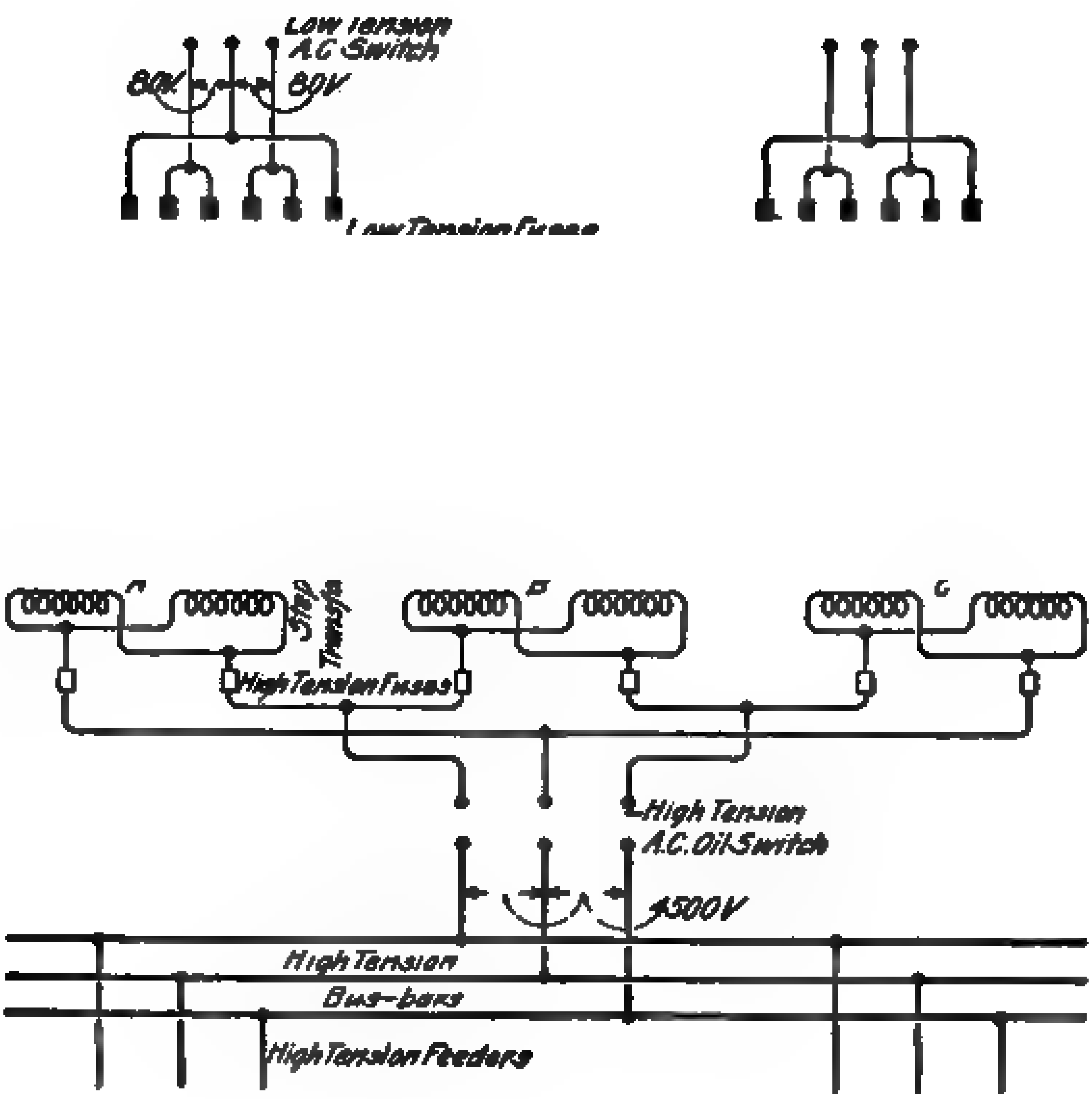

Low Tension
A.C. Switch
80V
80V
Step Transfs
High Tension Fuses
High Tension
A.C. Oil Switch
4500V
High Tension
Bus-bars
High Tension Feeders

FIG. 74

Chicago Edison Company. Two double-current generators are direct driven from a single steam engine and direct current at about 125 volts is supplied from the commutators and three-phase alternating current at from 75 to 80 volts from the collector rings *1*, *2*, *3*. The commutators are connected in series and are attached to the neutral bus-bar. The shunt fields of the generators are arranged for excitation from the direct-current bus-bars, and the + and – brushes of the pair of generators are connected to the + and – bus-bars of the three-wire system. In order to permit independent control of the alternating voltage, potential regulators are inserted, as shown. These regulators are of the induction type described later in connection with the use of rotary converters. After passing through a low-tension switch, the alternating current is led to the primaries of three step-up transformers A, B, C that raise the pressure from 80 volts to 4,500 volts. Each transformer is provided with two primary coils that are connected to two corresponding phases of the generators, as indicated by the numbers on the terminals of the primary coils. Each primary is provided with low-tension fuses. The two secondaries of each transformer are connected in parallel, and the three groups are Δ connected to the high-tension bus-bars. The alternating-current sides of the two double-current generators are therefore connected in parallel through the step-up transformers and feed into common high-tension bus-bars from which alternating current at high pressure is supplied to feeders running to distant centers of distribution. It is thus seen that by using double-current machines, a variety of service can be supplied from a single generating outfit and the generators kept loaded to best advantage.

85. The foregoing will give the student a general idea as to the arrangement of switchboards and the apparatus used in connection with them. The variety of apparatus used in switchboard work is so great that it is impossible to treat all types. Many stations have now become so large that it has been found necessary to make the switchboard

proper simply a place for grouping the small auxiliary devices needed to operate the main devices. It is now common to find field rheostats, field switches, main switches, etc. operated electrically or pneumatically from a distant point, and this method of operation has naturally introduced a large number of new switchboard appliances. Generally speaking, the tendency is to carry on this remote control by means of electricity rather than compressed air, as the electric current has proved just as reliable and is easier to apply. In some cases small electric motors are used for operating switches, rheostats, or other devices, especially where a rotary motion is required. In other cases a solenoid or electromagnet is simpler and more easily applied.

POWER TRANSFORMATION AND MEASUREMENT

TRANSFORMERS AND TRANSFORMER CONNECTIONS

1. Transformers vary somewhat as to their construction, but all have the three essential parts, i. e., the primary and secondary coils or groups of coils and the iron core that

FIG. 1

serves to carry the magnetic flux through the coils. Their construction also depends to some extent on whether they are to be used outdoors or indoors. Fig. 1 shows a typical transformer for outdoor use mounted on a pole in the

usual manner. Where transformers are large, say above 25 or 30 kilowatts capacity, it is not advisable to mount them on poles if it is possible to avoid it.

2. Primary Fuses.—Transformers are operated on constant-potential circuits almost exclusively; hence, if a short circuit occurs on either primary or secondary, there will be a heavy rush of current, which will do damage unless the transformer is instantly disconnected from the circuit. This is accomplished by inserting fuses in the primary between the transformer and the line. The fuses also protect the transformer against overloads. Fuses should be placed in each side of the primary, as indicated at *b*, *b*, Fig. 1, and should be so mounted as to be easily replaced by the lineman. Primary fuse blocks are made so that the fuse holder may be entirely disconnected from the primary mains when the fuse is being renewed; in other words, the fuse block serves the purpose of a switch as well as a fuse holder. In some cases the blocks are double-pole, but when the primary pressure is high, it is better to use two single-pole fuse blocks. Double-pole blocks are not recommended for transformers of greater capacity than 2,500 watts.

(a)

Fig. 2

Fig. 2 (*a*) shows a General Electric double-pole primary switch and fuse block, with one fuse holder (*b*) removed for replacing a fuse. The fuse lies in a deep slot *e* in the porcelain holder (*b*), and is fastened to the clips *d*, *d*. When the holder is in place, the clips engage with the terminals *f*, *f*, thus completing the connection to the transformer primary.

When a fuse is to be renewed, the porcelain base is pulled out and the lineman can replace the fuse without danger.

Fig. 3 shows a single-pole block made by the Stanley Company. In this case, the lid of the iron box is placed at the bottom and the fuse holder *A* is pulled out, thus breaking connection with the terminals *t*, *t*. The fuse *g* runs through

(b)

Fig. 3

a block of wood *h*, thus confining the arc and preventing it from arcing and burning the terminals *t*, *t*.

Where large transformers are operated in substations, automatic switches or circuit-breakers are used instead of fuses to disconnect the transformer from the line in case of a short circuit or overload.

TRANSFORMERS ON SINGLE-PHASE CIRCUITS

3. Transformers in Parallel.—Transformers may be connected in parallel so as to feed a single circuit, as shown in Fig. 4, but care must be taken when making the connections. Suppose that the two transformers are of the same type, so that they will both be wound alike. The primary terminals P_1 and P_3 must be connected to one of the mains, and P_2 and P_4 to the other main; the secondary terminals a and c will then have the same polarity at the same instant, which is the result desired. It will be noticed that, from the way in which the secondaries are connected, they oppose each other, and that little or no current will flow until the outside circuit is connected. In practice, it will be found that a current will flow between the transformers, but it will not be large. Suppose, however, that the secondary terminals are connected as shown in Fig. 5; the coils are now in series so that the E. M. F.'s act together to set up a current through the coils, thus resulting in a short circuit. In connecting up the secondaries, before making the final connections it is always well to make sure that the proper secondary terminals are being connected together. This can be found out by connecting two of them

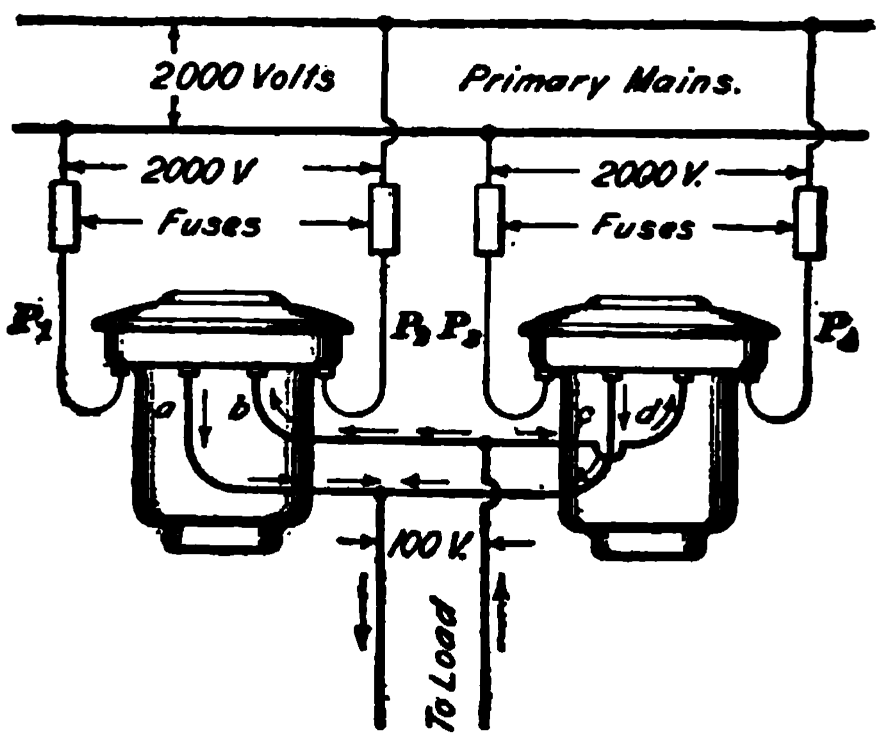


FIG. 4

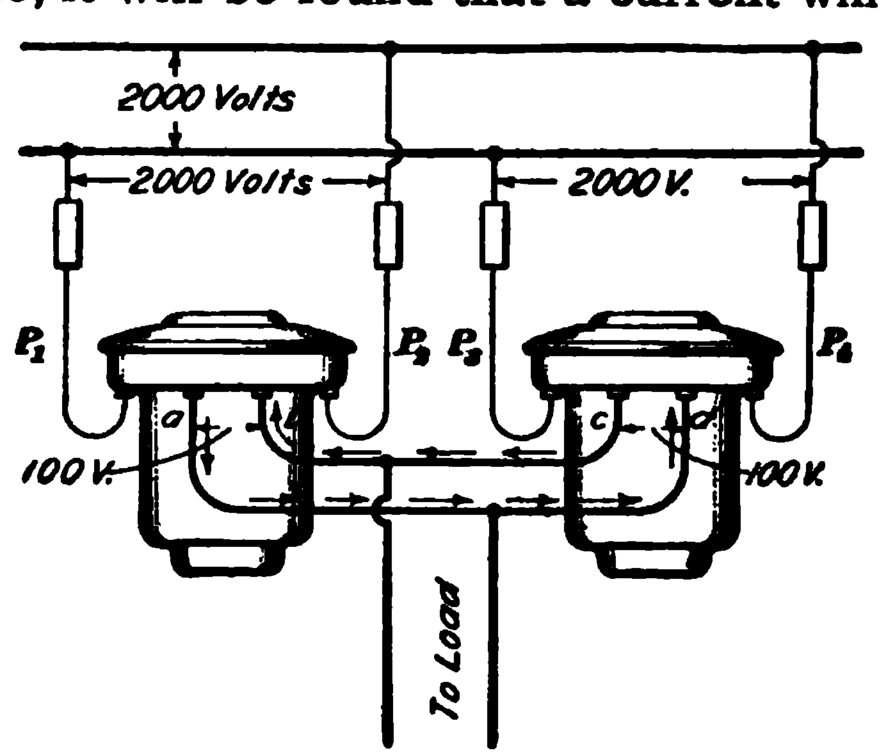


FIG. 5

together and then connecting the other two through a piece of small fuse wire or fine copper wire. If the fuse blows, it shows that the connections should be reversed. It is often more convenient to reverse the primary terminals than the secondary, especially if the latter have been joined up permanently. Reversing the primary has, of course, the same effect as reversing the secondary, and it is usually easier to carry out, because the primary connections are lighter and easier to handle.

4. Generally speaking, it is not advisable to operate several transformers in parallel, or *banked*, as it is sometimes termed. This is especially true if the transformers are

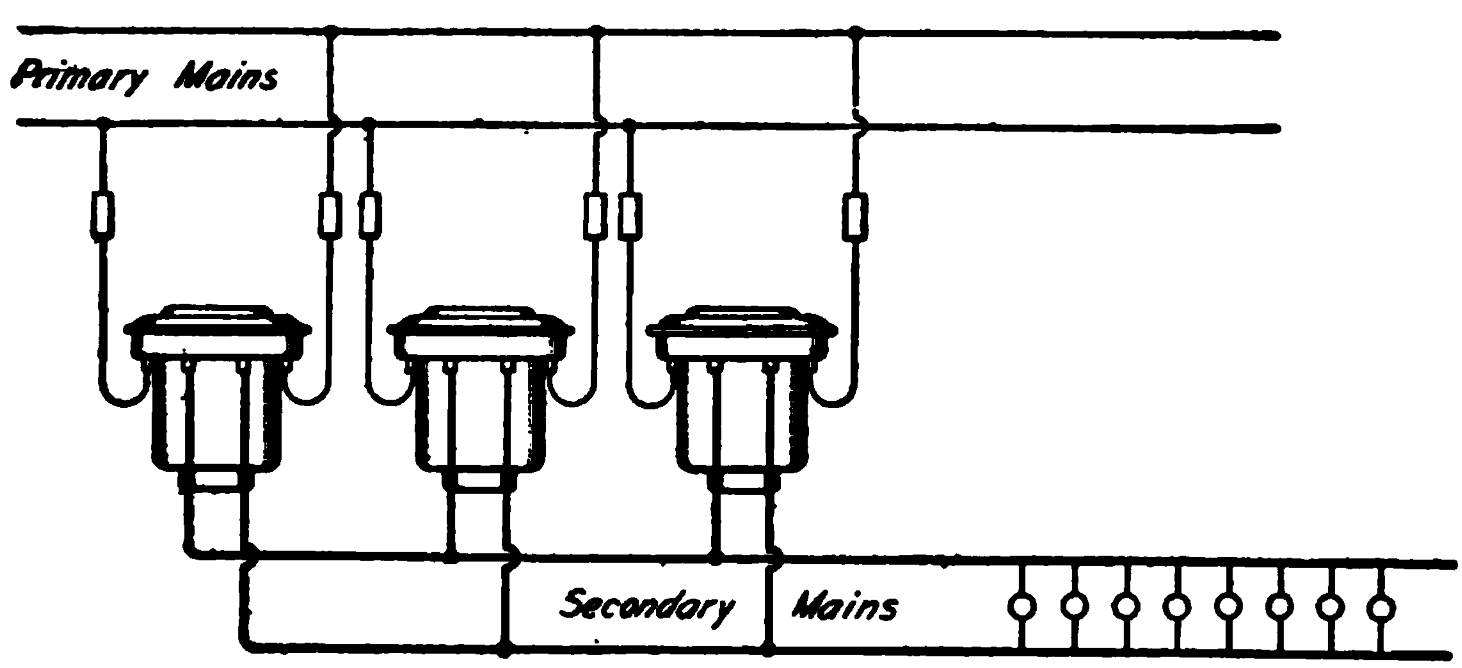


FIG. 6

small and scattered, as on many lighting systems, although it was occasionally done some years ago, when transformers were not made in large sizes. Suppose that a number of transformers are operating in parallel, as shown in Fig. 6. If they do not all have the same voltage regulation, the load may divide unequally between them and one or more of them take more than its share. The result is that the fuses of the heavily loaded transformer blow, and a heavier load is thrown on the remaining transformers, thus blowing their fuses. Of course, if the transformers are all of the same size and of similar design, such trouble is not very likely to happen; but it is better, if possible, to have each transformer supply its own share of the load, and if more capacity

is needed, to use one large transformer rather than a number of small ones.

5. Transformers are very often wound with their primaries and secondaries in two sections, so that they can be connected in series for high voltage and in parallel for low voltage. For example, in Fig. 7 the transformer is wound with two primary coils P, P_1, each designed for 1,000 volts and two secondary coils each wound for 50 volts. By connecting the coils P, P_1 in series, the transformer may be operated on 2,000-volt mains, and if the secondaries are also connected in series, it will supply current to 100-volt secondary mains. If the two primaries P, P_1 are connected in

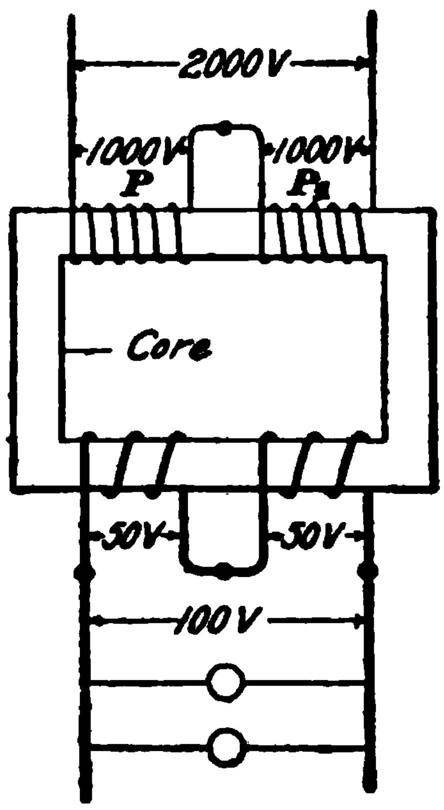


FIG. 7

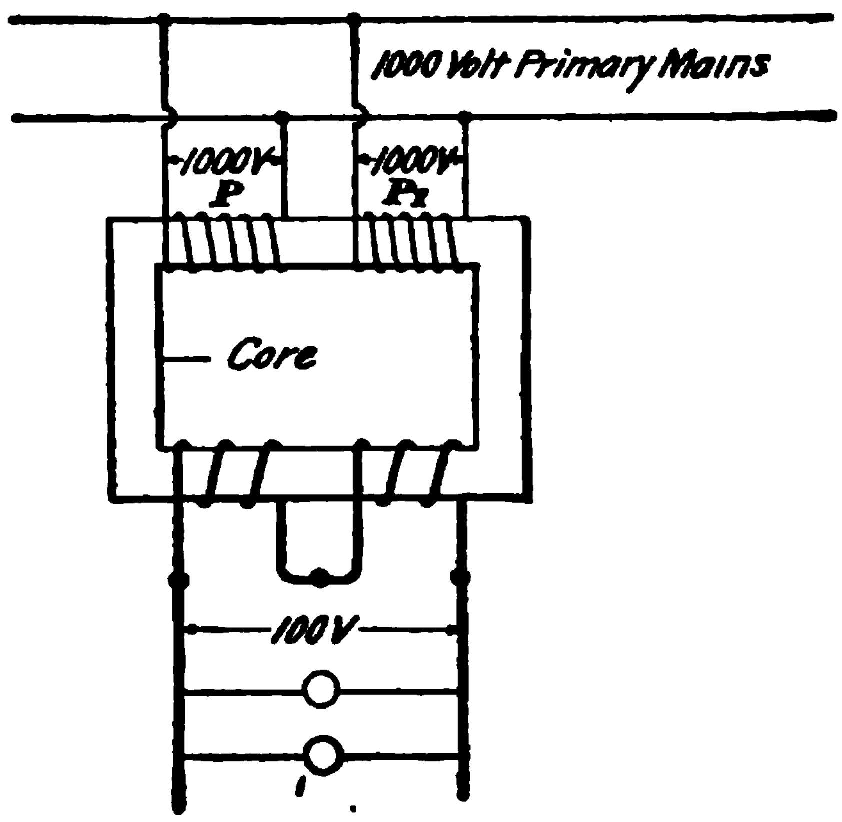


FIG. 8

parallel, as shown in Fig. 8, they may be operated on 1,000-volt mains, and if the secondaries are connected in series, they will supply current at 100 volts. If desired, the secondaries could be connected in parallel to supply current at 50 volts, but the 50-volt secondary circuit has practically gone out of use. A pressure of 50 volts was, at one time, used for incandescent lamps operated from transformers, but has given place to 100 to 110 volts, because the latter pressure requires less copper and it is now possible to obtain 100- to 110-volt lamps that operate fully as satisfactory as those made for 50 volts. Transformers are now

frequently wound so that they can be connected for either 104 or 208 volts on the secondary.

6. In many places, plants that were originally installed to operate at 1,000 volts primary pressure have been changed to 2,000 volts, in order to allow a larger load to be carried without increasing the size of the line wires. In such cases it has been common practice to connect old 1,000-volt transformers in pairs, as shown in Fig. 9.

7. Transformers on the Three-Wire System.—The general tendency is to use a few large transformers for supplying a given district rather than a number of small ones. Small transformers are wasteful of power, and though each in itself may not represent a very large loss, yet when a large number are connected the total amount of energy that might be saved during a year by using a few large transformers may be surprisingly large.

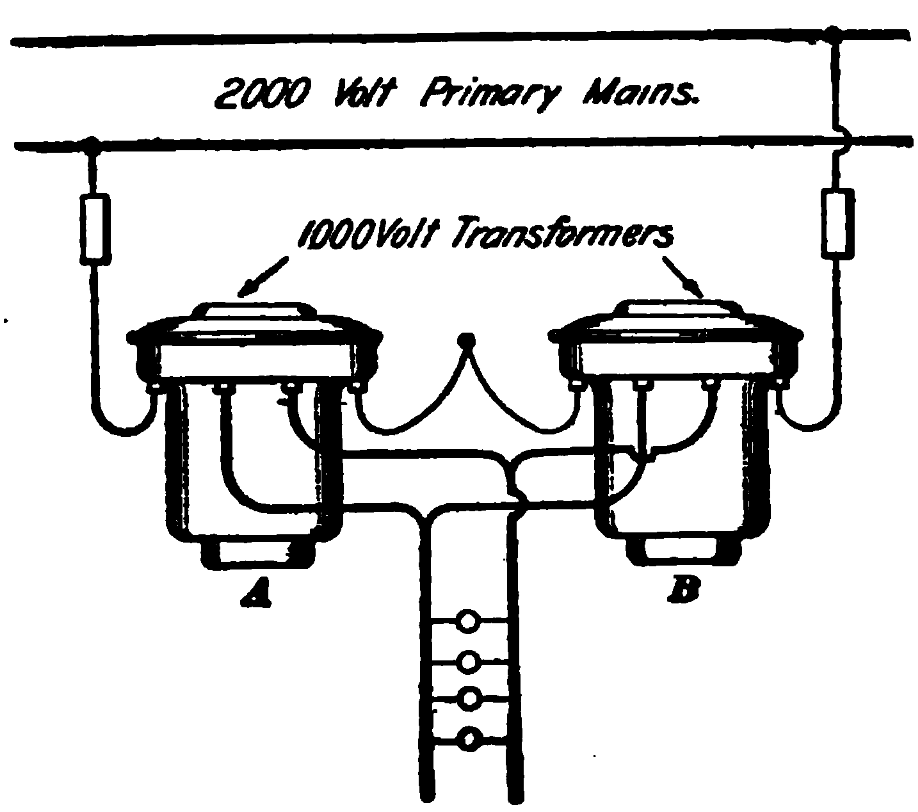


FIG. 9

Of course, in most cases where the customers are scattered it is impossible to avoid using a number of small transformers, but in business districts it is generally easy to use a few large transformers of high efficiency. These are frequently connected in pairs so as to feed into three-wire secondary mains *m*, *m*, *m*, as shown in Fig. 10. The primaries are connected directly across the line in parallel, and the secondaries are connected in series with the neutral wire connected between them at the point *o*. Care must be taken in connecting the secondaries to see that the terminals *a*, *b* are of opposite sign. If they are correctly connected, a pair of lamps *l*, *l* connected in series across the outside lines

should burn at full brightness. If they are wrongly connected, the lamps will not light at all, showing that terminals *a*, *b* are of the same polarity and that *c*, *d* are also the same, the secondaries being connected so that the two outside mains are of the same polarity with a common return wire in the middle. If two transformers are of the same style and make, the terminals of corresponding polarity will usually be brought out of the case in the same way. For example, in Fig. 4, terminals *a*, *c* would be of the same polarity at the same instant. It is always best, however, to test out the connections before connecting permanently, and this is

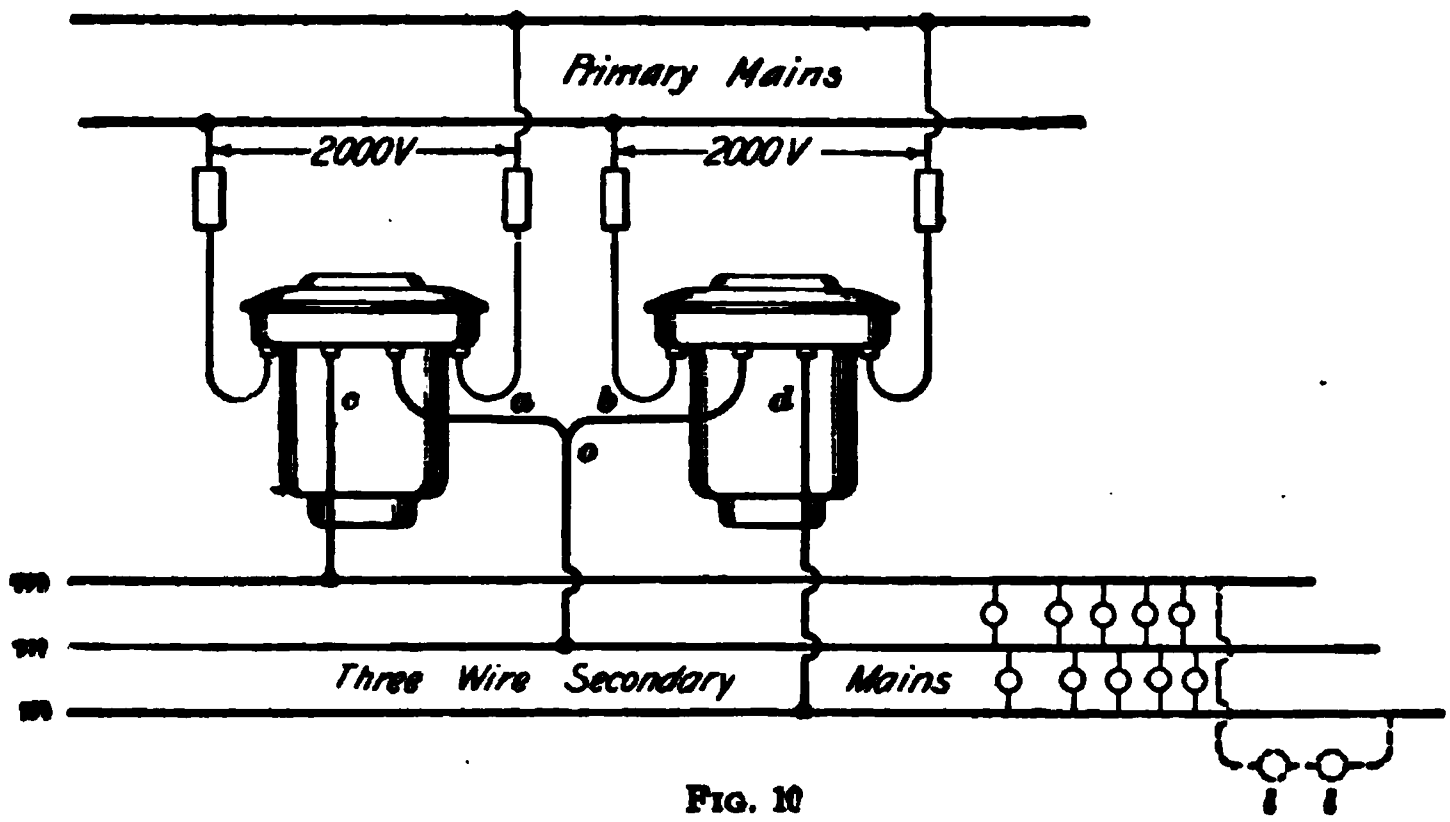


FIG. 10

especially necessary in case two transformers of different make or type are being dealt with.

8. Core-Type Transformers on Three-Wire System. When ordinary transformers of the core type are used to supply current to a three-wire secondary system, as shown in Fig. 11 (*a*), the voltage on the two sides of the circuit may become greatly unbalanced if the load is not equally divided. For example, in Fig. 11 (*a*) take the extreme case where the side *a* is not loaded at all. Secondary coil *s* will have no current and will therefore set up no counter magnetization, whereas coil *s'* will have a current due to the load on side *b*. Thus the magnetic flux in the two sides of the

core becomes unequal, as roughly indicated by the dotted lines, and the secondary E. M. F. is considerably higher on the side *a* than on the loaded side *b*. In order to overcome this difficulty, the General Electric Company wind the secondary in a number of sections *s, s, s, s*, Fig. 11 (*b*), and cross-connect these coils as indicated. The result is that no matter how unbalanced the load may be, the magnetizing effect of the secondary is the same on both cores and the voltage remains practically the same on both sides.

(*a*) (*b*)

FIG. 11

TRANSFORMERS ON TWO-PHASE CIRCUITS

9. As most two-phase circuits are operated with four wires, such a system is practically equivalent to two single-phase circuits. If it is necessary to connect two transformers in parallel, as shown at (*a*), Fig. 12, their primaries must be connected to the same phase. If they are connected to different phases, as indicated by the dotted lines running to phase *1*, a local current will flow through the secondary coils, because the secondary currents will not be in phase and there will be intervals when the E. M. F. of one will be greater than that of the other. The secondaries may, however, be connected in series, as shown at (*b*), forming a

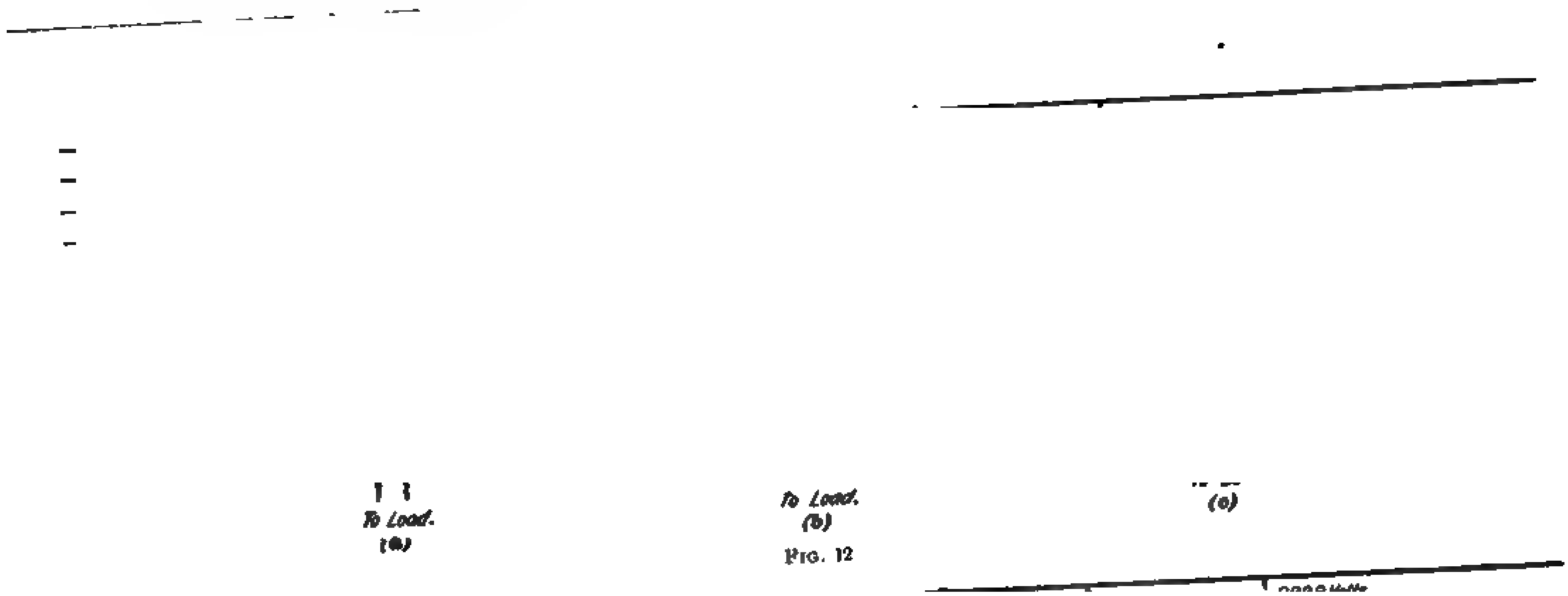


Fig. 12

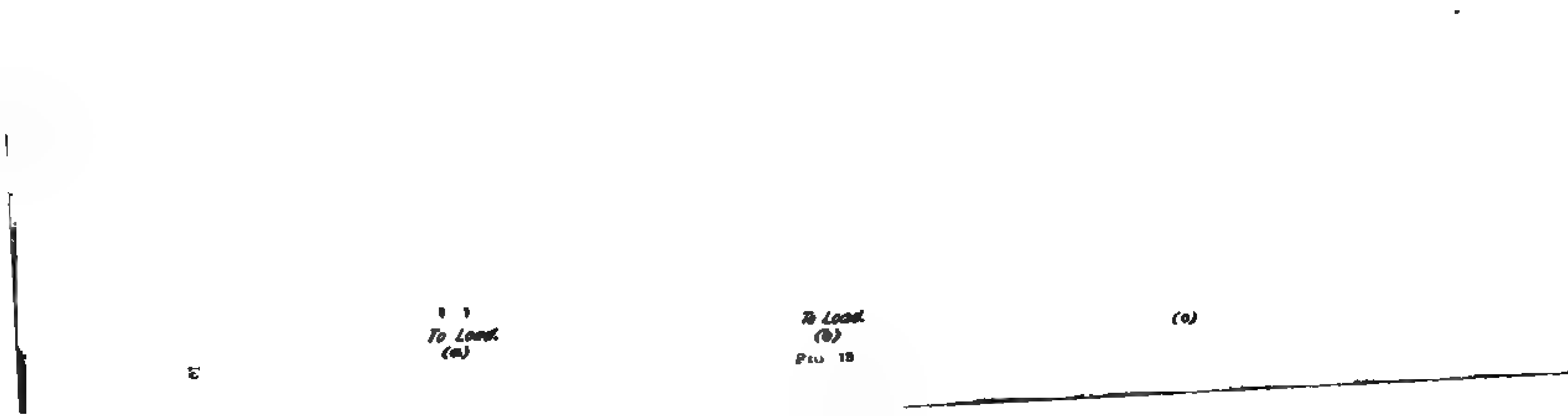


Fig. 13

kind of three-wire system. If the voltage of each secondary is E, the voltage between the two outside wires will be $E \times 1.414$. This is because the E. M. F.'s in the two coils are not in phase. This method of connecting transformers, however, is not to be recommended, as the voltages on the two sides of the three-wire system are apt to become unbalanced. If a three-wire system is desired, it is better to use the connections shown at (*c*), where both primaries are connected to the same phase. The E. M. F.'s in the two secondary coils are, in this case, in phase with each other and the pressure across the outside wires is twice that of one secondary coil.

10. In connecting transformers to a two-phase system, the aim should be to get the load on the two phases as nearly balanced as possible. Of course, where motors are operated, both phases are used, and, hence, there is not much danger of an unequal division of load. When lamps are connected, one transformer or set of transformers at one point on the circuit can usually be balanced against another group at some other point, so that the load as a whole will be equally divided. Fig. 13 shows different methods of connecting transformers on a two-phase system, using three line wires. In this case the central wire acts as a common return, and the voltage between the outside wires is 1.414 times that of each phase. The same remarks apply here as in the previous case, and the three-wire arrangement shown at (*b*) is not as generally satisfactory as that shown at (*c*). In both cases the primary pressure is shown as 2,000 volts, and transformers with a ratio of 20 to 1 are taken for the sake of illustration.

TRANSFORMERS ON THREE-PHASE CIRCUITS

11. Until recently it has been customary in America to use three single-phase transformers for transforming from one pressure to another on three-phase circuits; the three transformers may be connected up either Y or Δ. With the Δ arrangement, the power supply will not be entirely

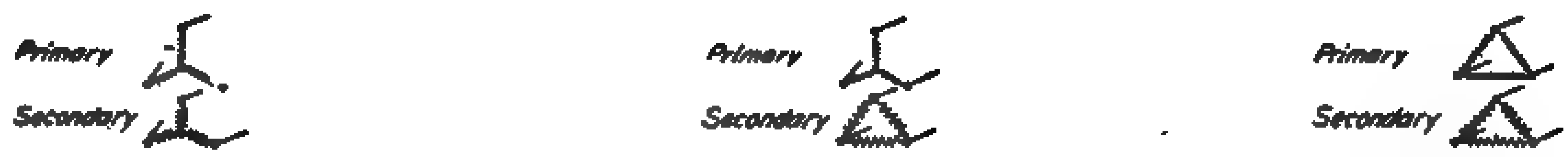


FIG. 14

crippled even if one of the transformers should become damaged; also transformers wound for standard line voltages can be used. In some cases, however, the primaries are connected across the lines according to the Y scheme, as shown at (*a*), Fig. 14, and since there are two primary coils in series between any pair of mains, the pressure on any one primary coil is less than that between the mains. When the primaries are Y connected, the secondaries are usually Y connected also, as shown at (*a*). Sometimes, however, the primaries are Y connected and the secondaries Δ, as shown at (*b*). If transformers having a ratio of 20 to 1 were connected in this way, the secondary pressure would not be the primary pressure divided by 20, i. e., 100 volts; but $\frac{100}{1.732}$, or 57.7 volts. In order to get 100 volts secondary with this scheme of connections, the transformers would have to be wound with a ratio of $\frac{20}{1.732}$ to 1, i. e., 11.55 to 1, approximately. Fig. 14 (*c*) shows transformers with both primaries and secondaries Δ connected. The arrangements shown at (*a*) and (*c*) are the ones commonly used for three-phase work, as scheme (*b*) either calls for special windings on the transformers or else gives rise to odd secondary voltages. If the primaries are to be Δ connected, each primary coil must be wound for the full-line voltage. If the primaries are Y connected, each primary coil is wound for the line pressure divided by 1.732. It is possible to use only two transformers on a three-phase system, as shown in Fig. 14 (*d*), but this arrangement is not, on the whole, as desirable as the Δ connections, because if one breaks down the service is crippled. It is equivalent to the delta arrangement with one side left out. The connections shown in (*c*) are used more largely than any of the others.

12. Phase-Changing Transformers.—By combining two E. M. F.'s that differ in phase by 90°, an E. M. F. of any desired amount and phase relation to the original E. M. F.'s can be obtained. For example, in Fig. 15 (*a*), suppose it is desired to produce an E. M. F. *E* of the amount represented

by the line oc and having the phase relation of oc. This E. M. F. can be regarded as made up of the two components ob and oa at right angles to each other; hence, if two E. M. F.'s E_1 and E_2, having the values represented by the lines ob and oa, and differing in phase by 90°, are combined, the result will be the required E. M. F. E. In Fig. 15 (b), A and B are the primaries of two transformers connected to a two-phase system. The E. M. F.'s E_1 and E_2 induced in their secondaries will therefore differ in phase by 90° and E_1 and E_2 can be made any desired value by suitably

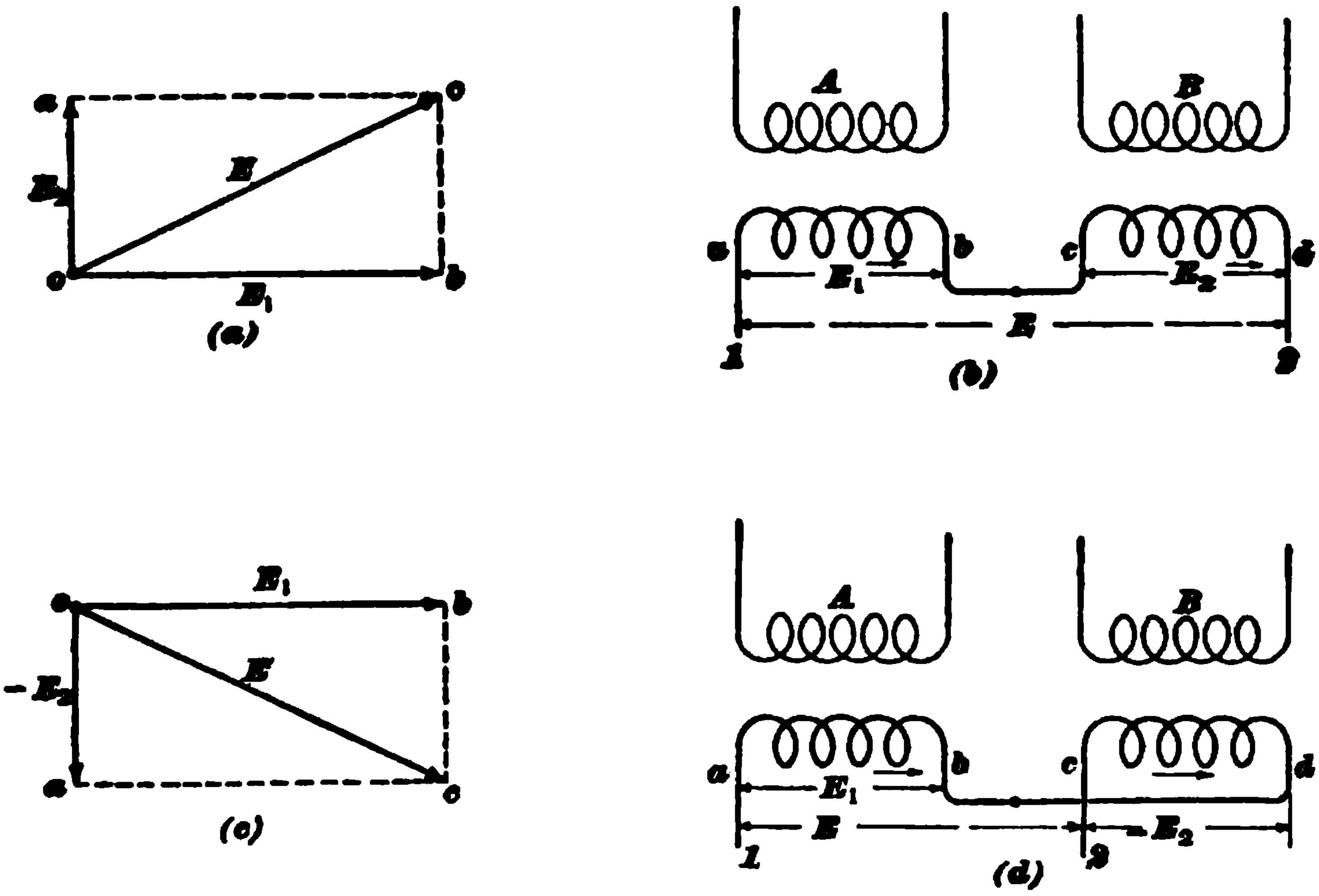


Fig. 15

proportioning the windings. If the two secondaries are connected in series, the E. M. F. between the lines will be the geometric sum of E_1 and E_2, as shown in (a). For example, in (b), in passing from line *1* to line *2* we go through each coil in the same direction; that is, we pass from a to b and from c to d in the direction indicated by the arrows. We will call this the positive direction. In (d), in passing from a to b we go through the coil ab in the positive direction, but, with the connections of the second coil reversed, as shown, we pass through cd from d to c against the arrow. The line oa (c) is therefore reversed with regard to its position in (a) and

the E. M. F. E between lines *1* and *2* is now denoted by the line oc, which is the same in amount as in (*a*), but has a different phase relation. Fig. 15, therefore, shows a method of obtaining a single phase current of any desired amount or phase relation, from two currents differing in phase by 90°.

13. Scott Two-Phase, Three-Phase Transformer. One of the most common examples of phase transformation is the changing of two-phase currents to three-phase, or vice versa, by means of the arrangement devised by Mr. C. F. Scott. In Fig. 16 (*a*), A and B are the primary coils of two transformers connected to a two-phase system. The secondary of A, i. e., the coil ac, is provided with a winding such

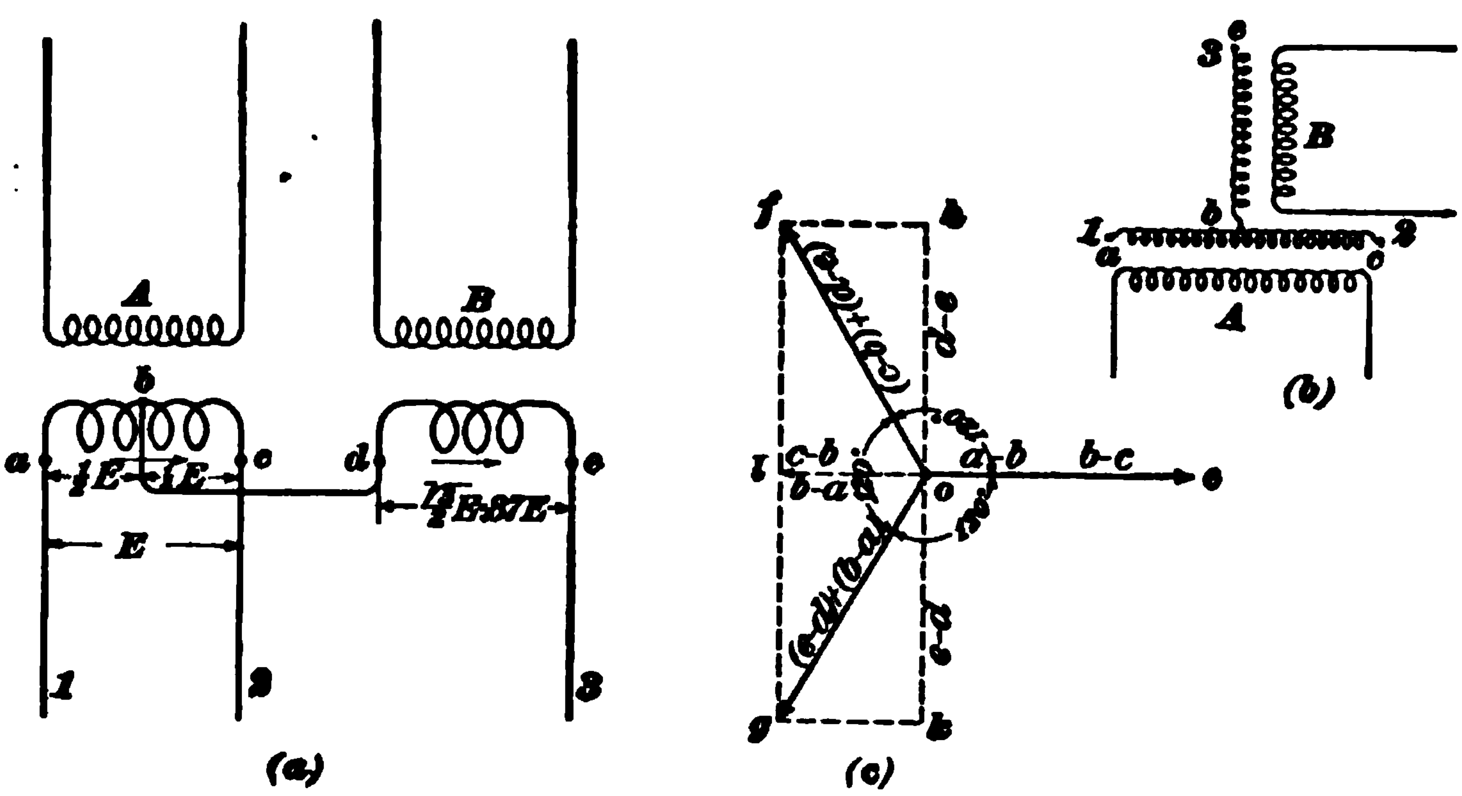


FIG. 16

that its voltage E will be the required voltage of the three-phase system. The secondary of B has $\frac{\sqrt{3}}{2}$ or .87 times as many turns as the coil ac, so that the voltage generated in it is .87 E. One end of coil de is connected to the middle point b of coil ac, as shown. With this arrangement of windings and connections, three currents differing in phase by 120° will be delivered to lines *1*, *2*, *3* when the primaries are supplied with two currents differing in phase by 90°. The same connections are shown in a simplified form in (*b*), the three-phase lines being attached to points *1*, *2*, and *3*. The E. M. F. between *1* and *2* is that generated in the secondary

ac. The E. M. F. between *2* and *3* is the E. M. F. generated in *bc* combined with the E. M. F. generated in *be*. The E. M. F. between *3* and *1* is that in *eb* combined with that in *ba*. It must be remembered that the E. M. F. in *be* is at right angles to the E. M. F.'s in *ab* and *bc*. Coming back to (*a*) and noting that the positive direction through the coils is marked by the arrows we can lay off the line *oe* in (*c*) to represent the E. M. F. between lines *1* and 2. The E. M. F. between points *a* and *b* is marked $a - b$ in (*c*) and is represented by one-half of *oe*. Also, the E. M. F. between *b* and *c* would be represented by $b - c$. The − sign does not here signify subtraction; it simply denotes that the E. M. F. referred to is taken between the points *b* and *c*. The E. M. F. between lines *2* and *3* is found by adding, geometrically, the E. M. F. $d - e$ to $c - b$. In passing from line *2* to *3* we pass from *c* to *b* against the arrow, or in other words the E. M. F. $c - b$ is the equal and opposite of $b - c$ and is represented by *ol* in (*c*) equal to one-half of *oe*, but drawn to the left of *o*. Coil *de* is passed through in the positive direction so that the E. M. F. $d - e$ will be represented by the line *oh* above the horizontal, and the E. M. F. between lines 2 and *3* will be the resultant of *ol* and *oh*, or *of*. The E. M. F. between lines *3* and *1* is $e - d$ combined with $b - a$. The E. M. F. between *e* and *d* is the equal and opposite of that between *d* and *e*; hence, it is represented by *ok*, which is equal and opposite to *oh*. The E. M. F. $b - a$ is equal to and in the same direction as $c - b$; hence, it is represented by *ol*, and the resultant of *ol* and *ok* is *og*, which is the pressure between lines *3* and *1*. The three secondary-line pressures represented by the lines *oe*, *of*, and *og*, are therefore of equal amount and differ from one another in phase by 120°, as is required for a three-phase system.

For long transmission lines, it is more economical to use the three-phase than the two-phase system; hence, where power is generated by two-phase alternators and stepped up for transmission over long distances, as, for example, at Niagara, the current is often transformed from two-phase to three-phase as just explained.

14. Capacity of Transformers on Two- and Three-Phase Systems.—When transformers are connected on a two-phase system each transformer must be of capacity sufficient to carry half the load. If the three-phase system using three transformers is used, each transformer must be capable of carrying one-third the load. When the transformers are used to operate induction motors, a safe plan to follow is to install 1 kilowatt of transformer capacity for every horsepower delivered by the motor. Thus, a 20-horsepower, two-phase, induction motor will require two 10-kilowatt transformers; a 30-horsepower, three-phase motor will require three 10-kilowatt transformers; and so on. Table I, issued by the General Electric Company, shows the size and number of transformers suitable for 60-cycle, three-phase induction motors.

TABLE I

CAPACITY OF TRANSFORMERS FOR THREE-PHASE INDUCTION MOTORS

Horsepower of Motor	Capacity of Transformers Kilowatts	
	Two Transformers	Three Transformers
1	.6	.6
2	1.5	1.0
3	2.0	1.5
5	3.0	2.0
7½	4.0	3.0
10	5.0	4.0
15	7.5	5.0
20	10.0	7.5
30	15.0	10.0
50	25.0	15.0
75		25.0

SUBSTATION EQUIPMENT

15. General Features.—The high-tension alternating current, for large transmission systems, is usually delivered to a number of substations rather than to scattered groups of transformers, and it is therefore necessary to study the equipment of these substations. In some cases the power is delivered from the substation in the shape of alternating current; in others, it is transformed to direct current and delivered to the various receiving devices, such as lamps, motors, etc. Part of the output may be delivered as direct current and part as alternating, either at the same frequency as the current generated in the main station or at a different frequency. It is thus seen that the character of the equipment in a substation may vary greatly, and will depend on the character of the service. If the power is used for operating a street railway where direct current at a pressure of 500 to 600 volts is required, the substation must be equipped with rotary converters for changing the alternating current to direct. Also, since the alternating current is transmitted at high pressure, it is necessary to provide transformers to step-down the incoming line voltage to an amount such that the converters will give the required direct-current voltage. The current can also be transformed from alternating to direct by using motor-generator sets, i. e., sets consisting of an alternating-current motor connected to one or more direct-current generators. Motor generators are more expensive than rotary converters of equal output, and are not quite so efficient; hence, the latter, especially in America, are much more generally used. For some classes of work, motor generators have advantages, and their operation on fairly high frequencies, over 60 cycles, is more satisfactory than that of rotary converters. They are used considerably on 60-cycle systems where the direct current is used for lighting work which requires close

voltage regulation. In a motor-generator set the two sides of the system are entirely separated, and disturbances on one side are not so liable to affect the other as with rotary converters. It is often practicable to wind the motor to take the high-tension line current without the intervention of step-down transformers, but even allowing for this the motor generator is not as economical, either as regards first cost or efficiency of operation, as the rotary converter. By using frequencies from 40 to 25 cycles per second, little difficulty is found in operating rotary converters; and at these frequencies they are largely used for the conversion of alternating current to direct current, or vice versa.

16. In some cases the output of a substation is delivered wholly as alternating current, and the substation contains simply the static transformers needed for raising or lowering the pressure, together with the switchboard appliances used to control the incoming and outgoing current. In substations where the output is in direct current supplied to lighting or railway systems, it is common practice to provide a storage battery in order to equalize the load, the battery being charged during intervals of light load and discharged when the heavy load comes on. The use of a number of substations supplied from one large central station results in a comparatively constant load on the central station, especially when storage batteries are used in those substations that are situated in densely populated districts and are called on for a very heavy output at certain hours during the day. One of the chief advantages in supplying the power from a large central station is the uniformity of load obtained throughout the day, thus allowing the generating units to be worked at their best efficiency.

The equipment of a substation may be conveniently considered under three heads, namely: (*a*) Apparatus for Controlling the Incoming Current; (*b*) Apparatus for Transforming the Current; (*c*) Apparatus for Controlling the Outgoing Current.

APPARATUS FOR CONTROLLING THE INCOMING CURRENT

17. The apparatus for controlling the incoming current is generally grouped on a regular high-tension switchboard, and is separated, at least so far as the high-tension parts are concerned, from the devices controlling the outgoing current. If lightning arresters are used, they are placed at a point near where the wires enter the building; very often they are placed in a separate building. The arrangement of the controlling devices, of course, differs in different stations, but the incoming lines should first pass through a circuit-breaker or main switch so that all current may be cut off from the station. In many cases oil switches are used, and are so arranged that they may be either opened by hand or automatically whenever the current exceeds the allowable amount. Arranged in this way, the switches fulfil the requirements of both a circuit-breaker protecting the apparatus in case of overload, and a main switch that can be opened by hand when desired. Switches of the air-break type and those in which the arc is broken in a confined air space are also made to operate automatically in case of overload; all of these types are in common use for protecting the incoming lines.

18. Time-Limit Relay.—In most substations, especially in those where rotary converters are operated, it is not desirable to have the circuit opened every time there is a momentary overload, because it allows the converters to fall out of synchronism and it takes some time to get things under way again. Besides, momentary overloads will not, as a rule, damage anything, while a long continued overload or short circuit will. For these reasons it is advisable to equip the circuit-breakers, or automatic switches, on the incoming lines with a **time-limit relay,** which controls the current in the tripping coils and will not allow the circuit to be opened until a certain interval of time has elapsed after the occurrence of the short circuit or overload. If the overload should pass off during this interval, the relay goes

back automatically to its initial position, and the circuit is not opened. If, however, the overload should continue beyond the limit for which the relay is set, contact is made and the tripping coils energized, thus opening the circuit.

Time-limit relays have been made in a variety of forms. Fig. 17 shows one type intended for two-phase or three-phase circuits and used on a number of the Niagara lines. The coils *a, a* are connected to the secondaries of current transformers whose primaries are in series with the main lines. If the current in either phase exceeds the allowable amount, either one or both of the armatures *b, b* are pulled down, thus releasing the clockwork mechanism *c*. If the short circuit or overload is not removed within the time limit for which the relay is set, say 3 to 5 seconds, the clockwork makes a contact that allows current to flow through the tripping coil of the circuit-breaker and thus opens the circuit. If the overload or short circuit should disappear during the time limit, the armatures *b, b* rise, thus preventing the clockwork from making contact. By equipping the various circuit-breakers on a system with this attachment, it is possible to set them so that in case a short circuit or overload occurs on a certain section, the circuit-breaker nearest that section will go out before those nearer the station. In other words, the breakers near the station are set so as to hold on for a longer interval than the more distant ones, thus preventing a shut-down of the machinery due to some fault on a distant part of the system. The time that must elapse before the relay makes contact

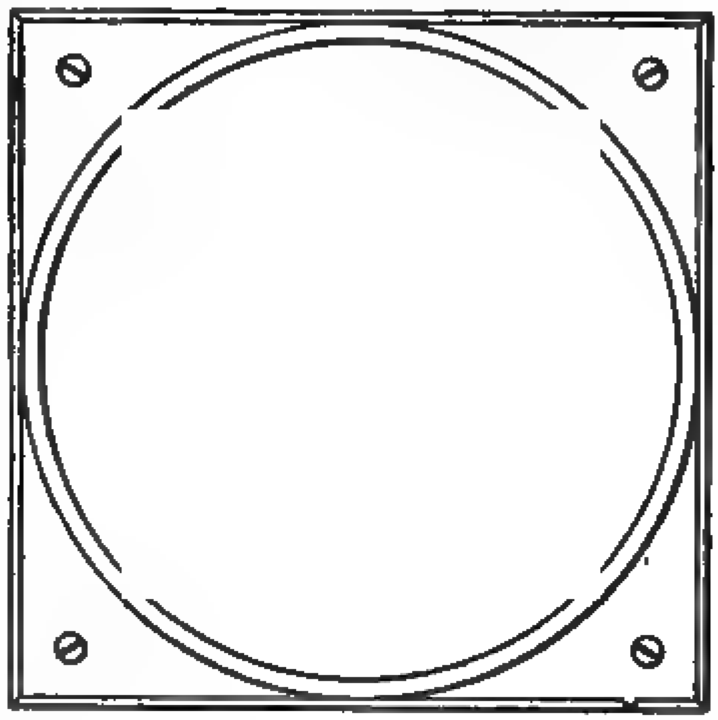


FIG. 17

can be adjusted by varying the angle made by the vanes *d*, Fig. 17. Fig. 18 shows the connections for one type of high-tension circuit-breaker operated by a time-limit relay. Current is supplied to the coils of the relay by the secondaries of the current transformers *A*, *A'*. The incoming lines are attached to studs *a*, *a* of the circuit-breakers, and the main current crosses over to studs *b*, *b* by way of the laminated contacts *c*, *c*, which are forced up against the studs when the breaker is set. Each pair of contact studs *a b* is shunted by a long enclosed fuse mounted in holders so that it can be quickly replaced by a new one in case it blows. When the breaker opens, thus withdrawing *c* from *a* and *b*, the main current flows momentarily through the fuse and the circuit is, therefore, finally opened by the fuse, which is capable of taking care of the arc. If the current becomes excessive and holds on beyond the time limit for which the relay is set, contact *d* touches *e*, thus allowing the cells *f* to send a current through the tripping coils of the breaker.

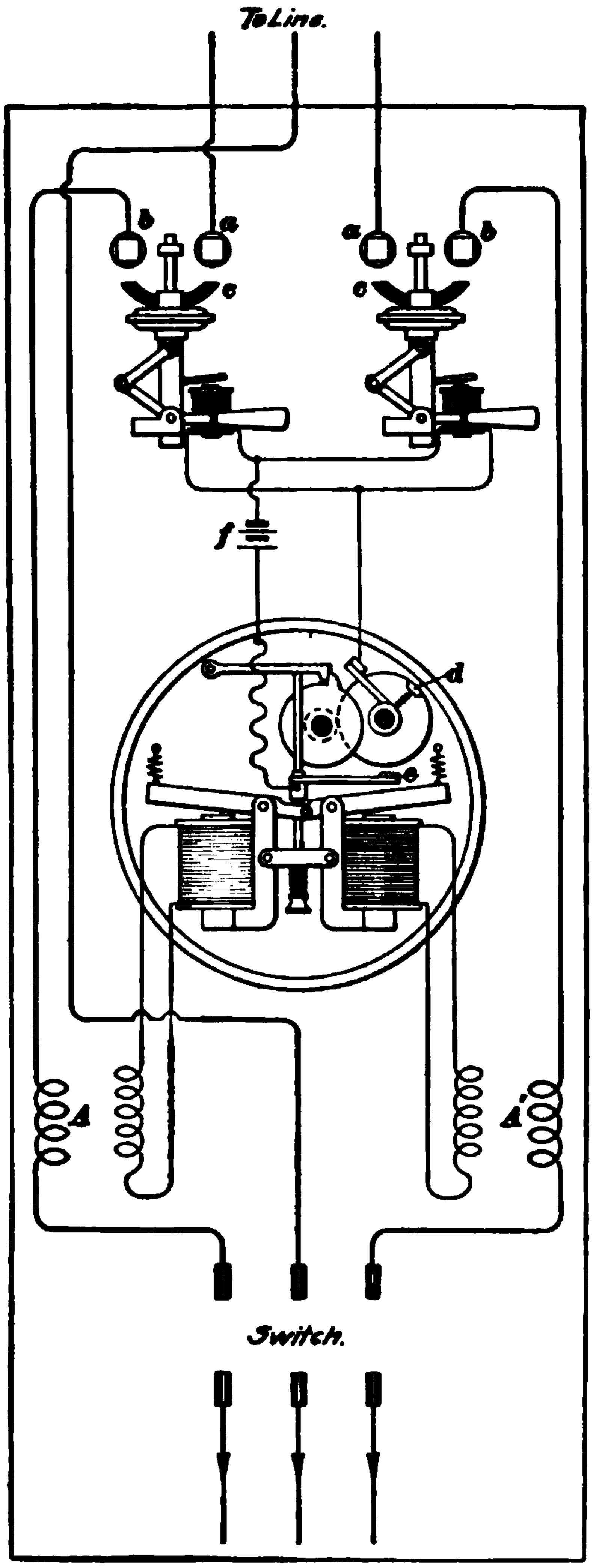


Fig. 18

19. Westinghouse Time-Limit Relay.—Fig. 19 shows a relay made by the Westinghouse Company. In this case the time-limit feature is regulated by means of a dashpot. A solenoid *a* is connected to the secondary of the current transformer, and the movable core *b* rests on a lever *c* pivoted at *d*. To the end of *c* is attached the piston rod *e*, which carries the piston of the dashpot *f*. The lever *c*, counterbalanced by the weight *g*, is normally held in the position shown in the figure, by the weight of core *b* resting on it. The arm *h*, also pivoted at *d*, carries the contact springs *k*, *l* and its position can be adjusted, up or down, by an adjusting screw on the cover of the instrument. Lever *c* carries a contact piece *m* that connects *k*, *l* if lever *c* rises far enough. When the current in *a* exceeds the allowable amount, core *b* is lifted, thus allowing the counterweight *g* to raise lever *c*. The movement of *c* is controlled by the dashpot *f* and the time during which the overload may exist before the circuit is opened is determined by the position of arm *h*. When lever *c* has moved high enough to make contact between *k* and *l*, the circuit-breaker is tripped and the main circuit opened. Should the overload pass off before the time limit is reached, *b* drops back and lever *c* is forced down before it has had time to make contact between *k* and *l*.

Fig. 19

20. Reverse-Current Relay.—In a large distributing system where a number of substations are connected to the main station, and to each other, by a network of cables, it is necessary to provide some means for preventing current

from flowing back toward a defective part and thereby maintaining a short circuit. This point will be understood more clearly by referring to Fig. 20, where *A* is the main station from which current is supplied to the substation *B*. Usually a number of cables in parallel are run between the main station and the substations in order to allow the use of cables of reasonable dimensions, and also to provide for uninterrupted service in case one or more cables should break down. Suppose that *c* and *d* represent two three-wire cables, supplying the substation *B* with three-phase current. When both are in use, the ends at the substation and at the main station are connected to common bus-bars. Suppose that a short circuit occurs at *f* on cable *c*. The rush of current through

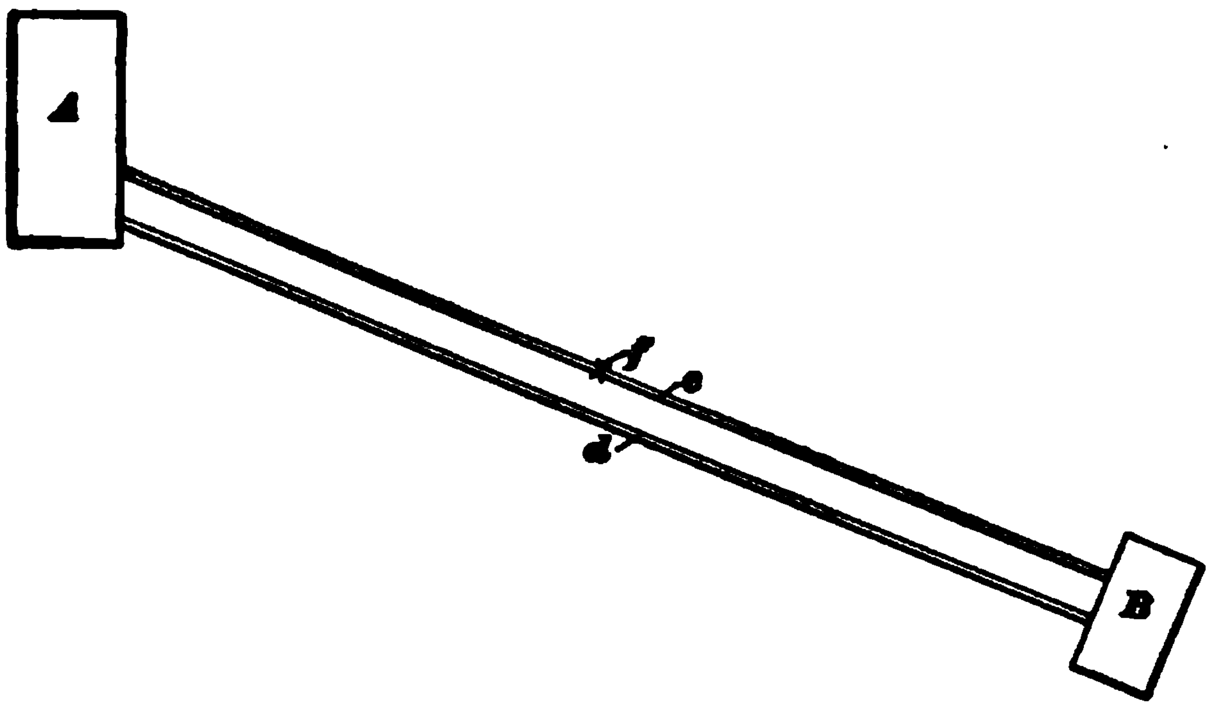


FIG. 20

the fault will, of course, open the circuit-breaker on cable *c* at the main station, but since *d* and *c* are connected together by the substation bus-bars, there is nothing to prevent a heavy current from flowing out over *d* and back through *c* to the fault *f*, thereby causing the circuit-breakers of cable *d* to open and completely shut off the power from the substation. In order to prevent this, **reverse-current relays** are installed at the end of the feeders, and their duty is to trip the circuit-breakers the instant the flow of energy through any of the cables reverses. Of course, where a substation is supplied by a single set of feeders and furnishes current to a secondary system which is not capable

of feeding current back to the line, reverse current relays are not needed.

Fig. 21 shows an arrangement of reverse-current relays used on the Niagara system, and also in a number of other installations. A, A are the circuit-breakers, and B, B the reverse-current relays. These relays are similar in construction to small direct-current motors having laminated fields. The field windings are excited by current from the secondaries of two potential transformers t, t', and the armatures are supplied with current from the current transformers c, c'. The armatures are not allowed to turn, since their motion is limited by an arm playing between two stops as shown. When the current is flowing in its normal direction from the cables to the bus-bars, the arm of the relay bears against the lower stop, which is not connected electrically to any other part. If, however, the flow of energy is from the bus-bars to the cables, the flow of current at each instant in the armature is reversed with respect to that in the fields, and the armature at once swings around in the opposite direction until the arm touches the upper stop, thus closing the battery circuit and tripping the circuit-breaker.

FIG. 21

This feeding-back action can also occur, if reverse-current circuit-breakers are not used, where a substation supplied through even a single set of feed-wires runs rotary converters which, on their direct-current side, are in parallel with storage batteries. If a short circuit occurs on the cable and it is cut off from the main generating station, the converters can still operate with direct-current furnished by the battery. They thus run inverted, taking the direct current from the batteries, converting it into alternating current, and feeding back to the line through the transformers. The current thus fed back to the fault in the cable will be very large, and may cause injury to the apparatus if means are not taken to prevent it by means of reverse-current circuit-breakers.

APPARATUS FOR TRANSFORMING THE CURRENT

21. If the current supplied from the substation to the consumers is utilized as alternating current, the substation is equipped with step-down transformers that supply alternating current directly to the secondary network. If the current is utilized as direct current, it is necessary to install rotary converters or motor generators in addition to the step-down transformers.

22. Substation Transformers.—Transformers used in substations do not differ materially from ordinary transformers except as regards their size and the methods used to secure cool running. They are usually of very large output as compared with those used for ordinary local lighting and power distribution. Their efficiency is very high, but on account of the comparatively small radiating surface that they present to the air, it is necessary to provide special means for getting rid of the heat, either by means of an air blast or by water that circulates through a coil of pipe placed in the upper part of the transformer case. With the latter method, the transformer case is filled with oil, and as the heated oil rises to the

upper part of the case it is there cooled by the water in the pipes, and descends to the lower part, thus keeping up a continuous oil circulation that carries the heat away from the coils and core.

Fig. 22 shows a Westinghouse 2,250-kilowatt substation transformer; (*a*) shows the coils and core assembled before being placed in the case. The core laminations *a*, *a* are built with openings *b*, *b* at intervals so that the oil can circulate through the core and conduct the heat from the internal parts. The primary and secondary coils are each wound in several sections in the form of large flat coils, which are then sandwiched together, making a construction that reduces magnetic leakage, and at the same time cuts down the voltage generated in any section of the winding. The ends of the coils project beyond the laminations at the top and bottom as shown at *c*, and the terminals of the coils lead to a terminal board mounted on top. The transformer is placed in a cylindrical tank made of riveted boiler plate, Fig. 22 (*b*), and is completely submerged in oil. Four coils of pipe placed in the upper part of the tank are connected in parallel by pipes *a*, *a* attached to common inlets and outlets. Each coil is provided with a valve, so that in case it becomes defective, it can readily be cut out without disturbing the flow of water through the others. This transformer, being of very large output, has an efficiency of 98.63 per cent. at full load, 98.2 per cent. at half load, 97.2 per cent. at quarter load, and 98.5 per cent. at one-half overload.

Fig. 23 shows a sectional view of an air-blast transformer of the General Electric type. The construction of the coils *A*, *A* and core *B*, *B* is such that air spaces are left between the parts, and the transformer is mounted over an air chamber in which about ½ ounce air pressure is maintained by motor-driven fans. The air passes through the openings in the core, between the coils, and out at the top and sides; suitable dampers are provided by means of which the flow can be regulated. This makes an efficient and cleanly method of cooling large transformers.

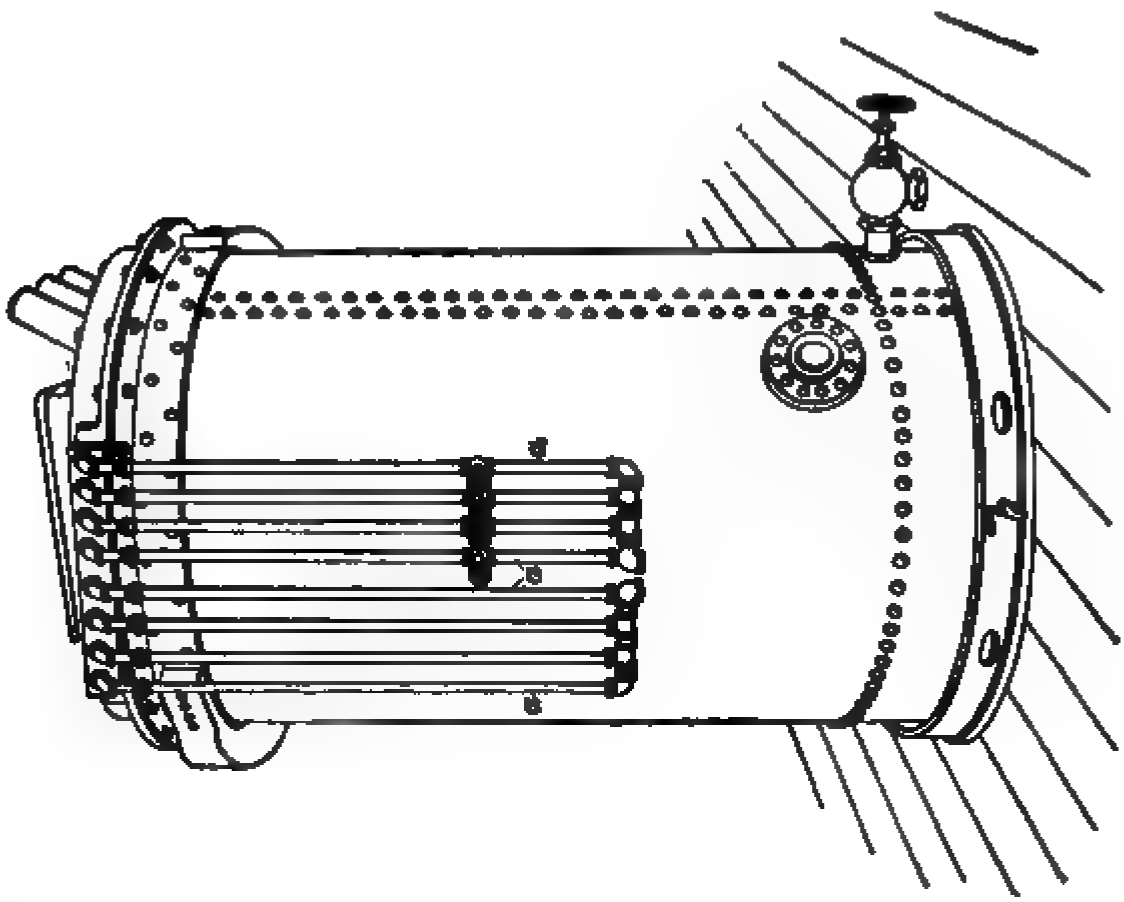


Fig. 22 (b)

Fig. 22 (a)

Fig. 24 shows a group of nine air-blast transformers of 150 kilowatts each. A motor-driven fan is mounted at each end of the chamber and either fan has sufficient capacity to keep the transformers cool, thus providing a reserve blowing outfit in case one breaks down. The power required to operate the fans does not usually exceed one-tenth of 1 per cent. of the transformer output.

23. Polyphase Transformers.—In Europe, two-phase and three-phase transformers have been quite commonly used, and three-phase substation transformers are now manufactured in America. By using polyphase transformers, a saving in material is effected, thus reducing the cost per kilowatt. Also, a considerable saving in space is gained because a polyphase transformer, of given output, takes up less room than an equivalent output in single-phase transformers. This is an important consideration in stations located in large cities. On the other hand, the use of single-phase transformers is somewhat safer, because if a breakdown occurs it is liable to damage but one of the transformers.

FIG. 25

Fig. 25 shows the general arrangement of a three-phase core-type transformer. The primary and secondary coils, which are wound on the cores *A*, *B*, *C*, may be connected Y or Δ. The magnetic flux in the core follows the same changes as the currents. Each core acts alternately as the return path for the flux in the other two cores, just as each

line wire acts alternately as the common return for the other two in a three-phase line. The iron in the core is thus worked

Fig. 24

to better advantage than when three separate single-phase transformers are employed. A two-phase transformer can be made by winding coils on cores *A* and *C* and leaving core *B* without coils; *B* will then act as the return path for the fluxes set up by the coils on *A* and *C*. Since these two fluxes will differ in phase by 90°, the resultant flux in *B* will be $\sqrt{2}$ times the flux in *A* or *C*; hence, for a two-phase transformer, the central core *B* will have a cross-section $\sqrt{2}$ times that of *A* or *C* instead of being equal as shown for the three-phase transformer.

Fig. 25

ROTARY CONVERTERS

24. The main features of **rotary converters** were described in connection with alternating-current apparatus. The types generally used are the two-phase or quarter-phase, three-phase, and six-phase; in America, the three-phase converter is used more largely than either of the others. Each converter is provided with its transformer or set of transformers in case it is necessary to step-down the line voltage. In some stations, notably in railway power plants, the alternating current is generated at low pressure when the

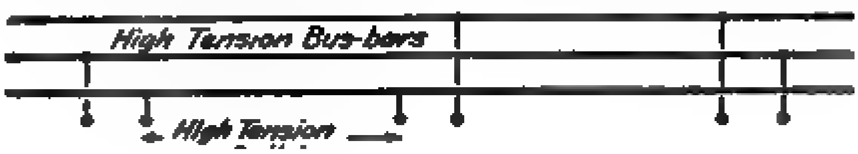


Fig. 26

greater part of the power is used near the station. In such plants, the near-by portions of the system are supplied with direct current from rotary converters placed in the main station and supplied with current directly from the alternators without the intervention of step-down transformers. If a very large percentage of the power was used as direct current for near-by points it would probably be cheaper to install double-current generators and dispense with the converters. In the majority of cases, however, where

converters are used it is necessary to use transformers to supply a suitable voltage.

25. Connections for Six-Phase Rotary Converters. It has been shown that the output of a rotary converter is increased by increasing the number of phases, and six-phase converters are used to a considerable extent, especially where the machines are of large output. Six phases are easily obtained from three by providing each of the three transformers with two secondary coils, as shown in Fig. 26. Coils *1*, *3*, and *5* are connected Δ, as also are *2*, *4*, and *6*, one group being reversed as regards the other, thus giving the double-delta arrangement indicated in Fig. 27. The collector rings are attached to the points *a*, *b*, *c*, etc., thus supplying the converter with six currents differing in phase by 60°. The use of six phases introduces some additional complication in the connections between the transformer secondaries and the converter, and also requires six collector rings, but this extra complication is more than offset by the increased output of the converters. Sometimes switches are inserted between the transformer secondaries and the converter, but more often the switching is done on the primary side because the secondary current is usually large and the switching devices correspondingly heavy.

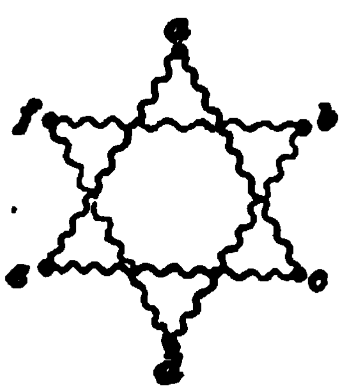


FIG. 27

26. Voltage Regulation of Rotary Converters. Usually it is necessary to arrange converters so that their direct-current voltage can be increased with increase of load so as to keep the voltage constant at distant points on the system. It was pointed out in connection with the theory of rotary converters, that the voltage of the direct-current side could be raised or lowered within certain limits by changing the field excitation of the converter. The change in field excitation with increase in load is usually obtained by providing the machine with a compound field winding similar to that on a compound-wound, direct-current dynamo. If the load were not of a suddenly fluctuating character, the

necessary field regulation could be obtained by adjusting the rheostat in the shunt-field circuit, and a series-field winding would not be needed.

In order to admit of voltage regulation by varying the field strength of the converter, it is necessary to have a certain amount of reactance on the alternating-current side; this can be provided by inserting reactance coils between the transformers and the collector rings, as shown in Fig. 28. *A*, *B*, and *C* are the step-down transformers, and *D* is a laminated core on which the three reactance coils are wound.

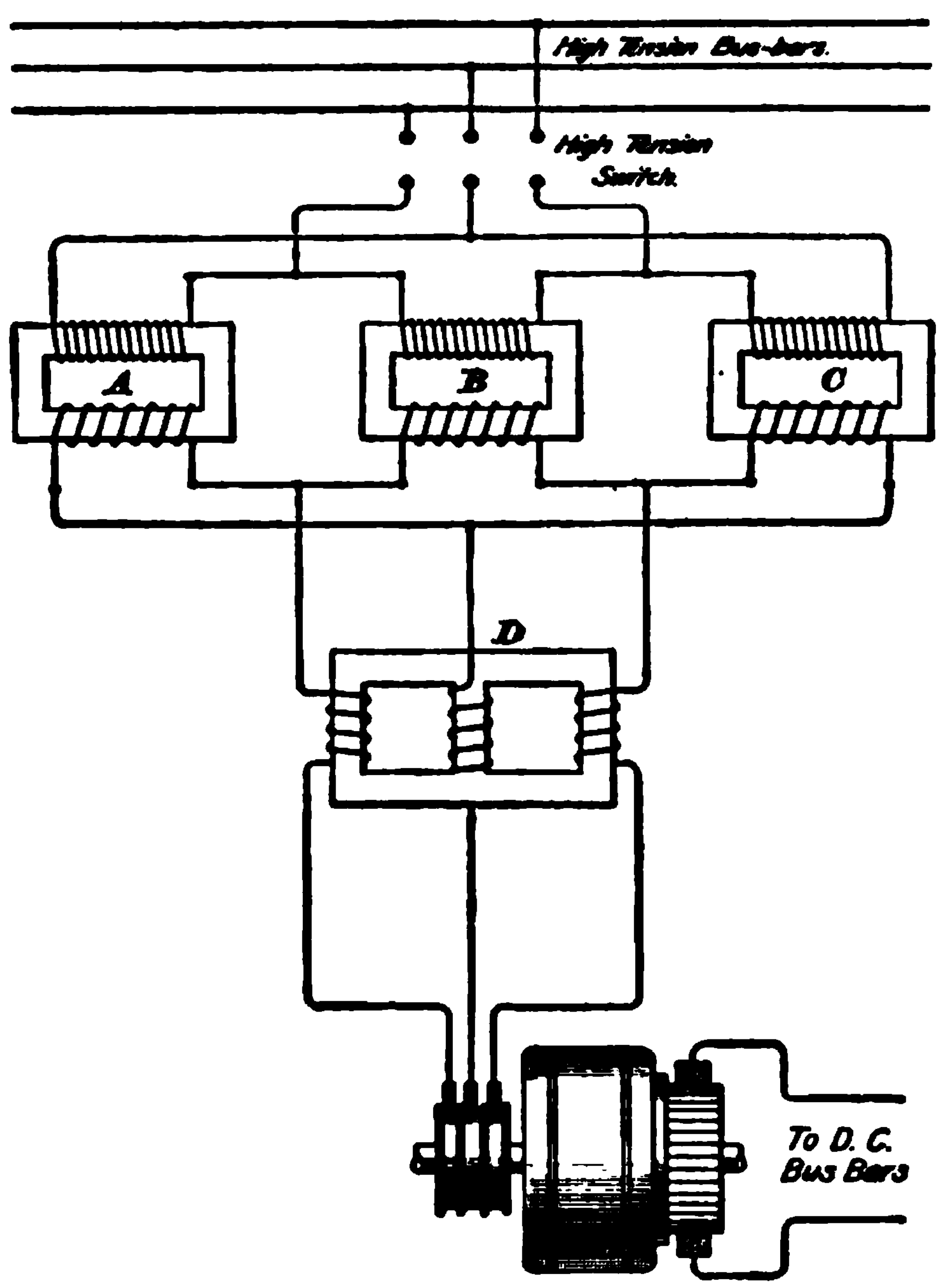


Fig. 28

Another method of regulating the voltage of a converter is to provide the transformer secondaries with a number of taps connected to a multipoint switch, thus allowing the number of secondary turns to be varied. This method does not admit of as gradual a variation in voltage as some others, but it is simple and well adapted to cases where a considerable range in voltage regulation is desired.

A third method of regulation is to insert a *potential regulator* between the transformer secondaries and the collector rings. These regulators are made in a variety of forms, but they are nearly always some special type of transformer; the general features of this method of regulation will be understood by referring to Fig. 29. The secondary coils *s*, *s*, *s* of

the regulator are connected in series with the leads running between the transformers and the converter; the primaries *p*, *p*, *p* are connected across the three phases as shown. Since the secondary coils are in series with the mains, it is evident that their E. M. F.'s will be added to or subtracted from those of the main transformers. If provision is made for varying the value of the E. M. F.'s generated in *s*, *s*, *s*, or for changing their phase relation with respect to the E. M. F.'s of the main transformers, the E. M. F.'s applied to the converter can be raised or lowered by an amount equal to the pressure generated in *s*. In some regulators, the effective E. M. F. of the series-coils is varied by cutting turns in or out, as, for example, in the Stillwell regulator. Provision is also made for reversing the E. M. F. of the coil with respect to the circuit, so that the main E. M. F. can be raised or lowered. Another scheme is to arrange the magnetic circuit or the secondary coil so that by moving the coil or a portion of the core, the amount of magnetic flux passing through the secondary can be varied, thus changing the value of the induced E. M. F.

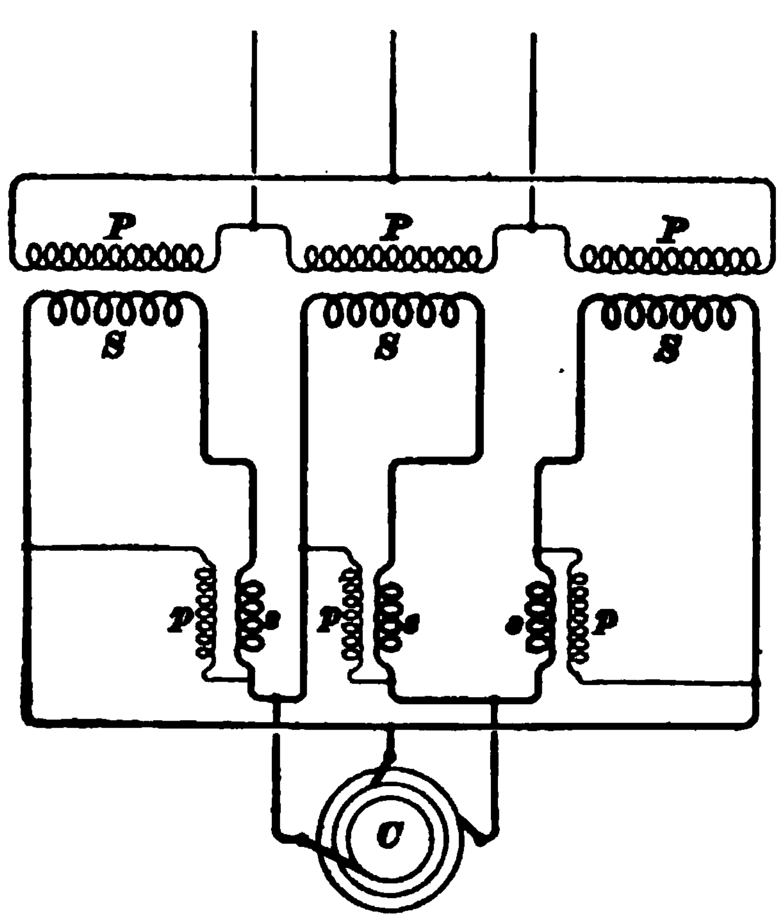


FIG. 29

27. Fig. 30 (*a*) shows the general appearance of a three-phase induction potential regulator made by the General Electric Company and intended for regulating the voltage of a rotary converter. The stationary part of this regulator, Fig. 30 (*b*), consists of a laminated structure *a*, *a* with inwardly projecting teeth exactly similar to the field of an induction motor. This is provided with distributed bar windings *b*, *b*, which are connected in series with the mains

running to the converter. The primary consists of a laminated core *c*, *c* similar to the armature core of an induction motor; this is mounted on a vertical shaft *s* so that the core can be turned through a limited range by means of the hand wheel *h*, which operates a worm engaging with a segmental gear attached to *s*. The primary is provided with three windings distributed in the slots, and connected across the phases as described in connection with Fig. 29. In this type of regulator, the field set up induces an E. M. F. of constant amount in each secondary winding. The adjustment of the amount of "boost" is effected by varying the phase relation of the secondary E. M. F. to that in the primary. For example, if the secondary induced E. M. F. and the primary E. M. F. are in phase, i. e., with the north and south poles of the primary and secondary windings facing each other, the maximum amount of increase in voltage will be obtained. With the secondary E. M. F. exactly opposite in phase to the primary, the E. M. F. will be lowered by an amount equal to the induced E. M. F. For intermediate positions of the primary, intermediate phase relations are obtained and the E. M. F. will be raised or lowered by an amount corresponding to the value of the component of the secondary E. M. F. that is in phase with or in opposition to the line E. M. F. With a regulator wound for four poles, a movement of 90° will give the total range of voltage, and as the movement is not large the current can be conducted into the primary by means of flexible cables. These regulators are also arranged for operation by means of a small motor, thus allowing them to be placed at some distance from the switchboard.

28. **Methods of Starting Rotary Converters.**—In cases where direct current is available, rotary converters are usually started by driving them up to synchronism as direct-current motors. In many substations, storage batteries furnish a source of direct current that is available at all times for starting purposes. Of course, when one converter has been started it can be used as a source of direct current for starting others. In some cases, where a storage battery is

not available, direct current is obtained from a small motor-generator set consisting of an induction motor coupled to a direct-current dynamo. One advantage in starting from the direct-current side is that the direct current furnished by the converter is always of the same polarity, that is, the positive terminal, say, is always positive; whereas, when the converter is brought up to speed by allowing alternating current to flow through the armature, the terminal may be positive at one time, and the next time the converter is started it may show a negative polarity.

(a)
Fig. 30

When starting from the alternating-current side, the field is unexcited and when the current is first thrown on, the voltmeter connected to the direct-current side will show no

(b)
Fig. 30

deflection because the E. M. F. between the direct-current terminals is then rapidly alternating, and, hence, will not effect a voltmeter of the Weston direct current or similar type except perhaps to cause a trembling of the needle. As the converter comes up to speed, the frequency on the direct-current side becomes slower and the voltmeter needle begins to vibrate, its rate of vibration becoming slower as the converter gets more nearly into synchronism. At exact synchronism, the E. M. F. on the direct-current side is steady; hence, the voltmeter reading becomes steady. The field should be excited just before synchronism is attained, and the polarity of the direct-current terminals will depend on which side of the zero the voltmeter pointer happens to be when the field is excited. If the exciting switch is closed with the pointer on the wrong side, the polarity will be wrong.

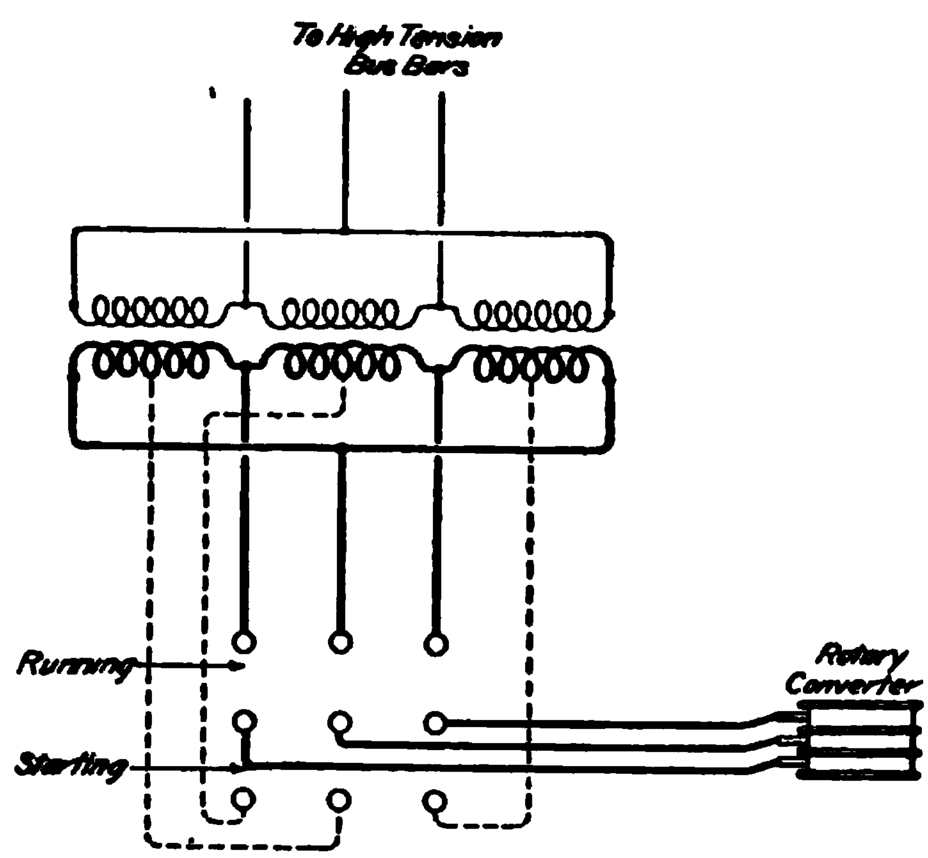


Fig. 31

Another objection to starting with alternating current is that when the current first flows through the armature it sets up an alternating flux through the field coils that may induce extremely high E. M. F.'s in them. Since the field coils are usually connected in series, the total E. M. F. generated may be so high as to endanger the insulation of the coils. When this method of starting is used, it is customary to install a special switch for disconnecting the field coils from each other while the converter is being started. Just before synchronism is attained, the coils are connected in the usual way and supplied with exciting current. It is not usually advisable to apply the full alternating-current voltage to the collector rings until the machine has come up

to speed, because the full voltage will give rise to an objectionable rush of current. To cut down the voltage at starting, a starting compensator similar to that used in connection with induction motors is suitable, but a simpler arrangement is to bring out taps from the transformer secondaries and connect these to a double-throw switch so that in one position of the switch the converter receives half the secondary voltage, while in the running position the full voltage is applied. Fig. 31 shows this arrangement.

One considerable advantage in starting from the alternating-current side is that the converter does not have to be synchronized; it is brought into synchronism by the alternating current. This is an important consideration when a machine must be started in a hurry. Starting from the alternating-current side does not give rise to undue disturbances if the frequency of the converter is fairly low, say 25 cycles per second. On many switchboards connections are provided so that the converters may be started with either direct or alternating current.

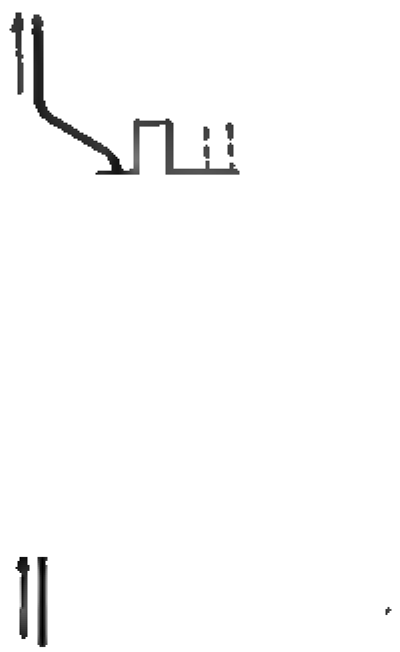


Fig. 32

When the converter is started from the direct-current side, it is necessary to insert a resistance in the armature circuit. Fig. 32 shows a type of starting rheostat used for this purpose. On account of the unequal lengths of the switch clips, the three sections of the resistance are successively short-circuited as the switch is closed. As the converter starts up as an unloaded direct-current motor, it comes up to speed quite rapidly and a simple switch giving four or five resistance steps is sufficient.

Where direct current is not available, the converter may be started by means of a small induction motor having its armature mounted on an extension of the shaft. This method is used by the Westinghouse Company. It involves the use of a small auxiliary motor on each converter, and if the station contained many machines it might be cheaper and more satisfactory to install a small motor generator set and start from the direct-current side.

29. Synchronizing Rotary Converters.—Rotary converters and synchronous motors are synchronized with the

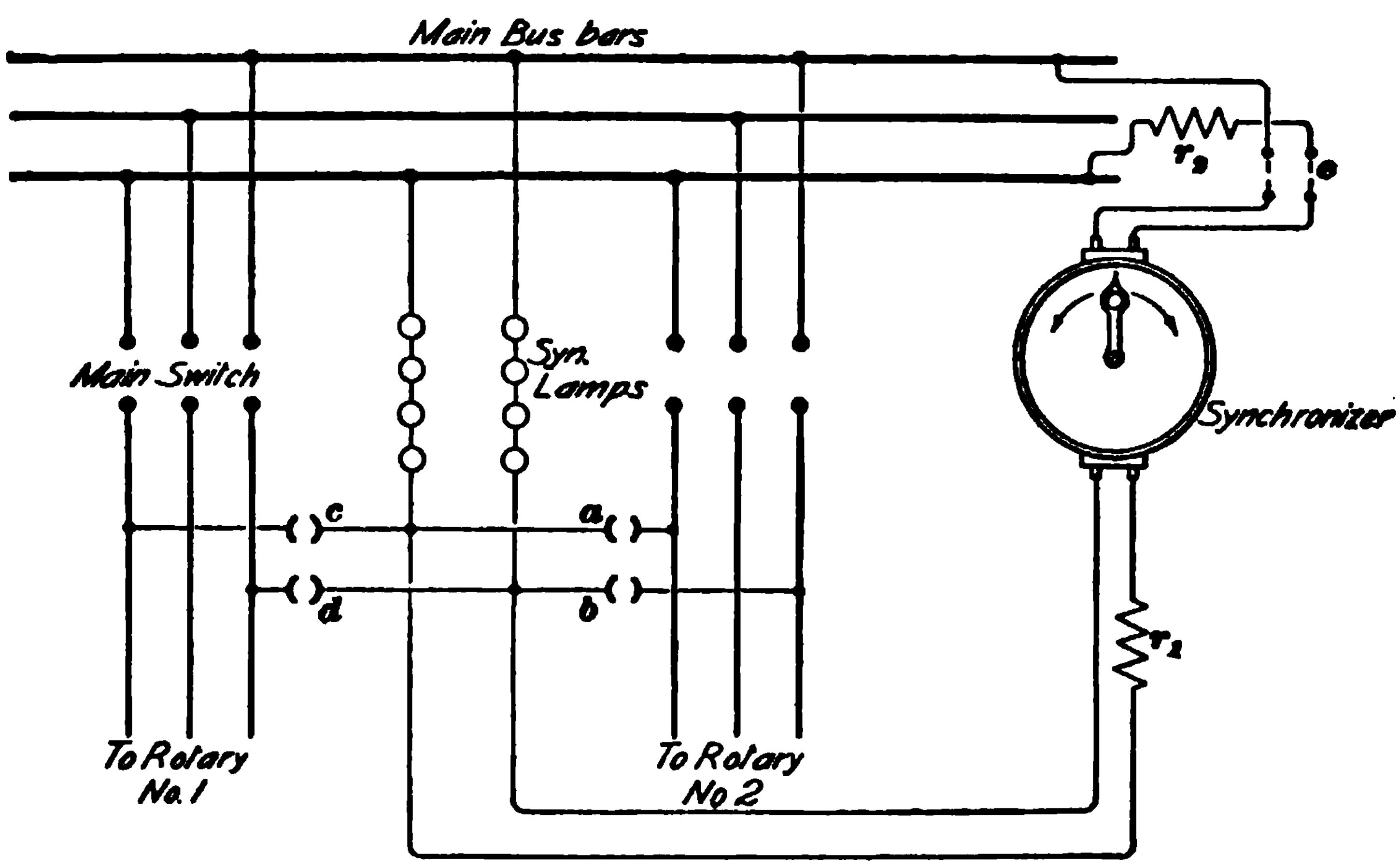


FIG. 33

line E. M. F. in the same way as an alternator is synchronized with the bus-bar E. M. F. Lamps, voltmeters, or synchronoscopes may be used to indicate the point of synchronism. Fig. 33 shows a Lincoln synchronizer used to indicate when either of two rotary converters is in synchronism. In this case the converters are fed directly from low-pressure bus-bars and potential transformers are not needed in connection with the synchronizer. When the pressure is more than 400 or 500 volts, potential transformers should be used. Synchronizing lamps are also provided, enough lamps being connected in series to stand

the voltage. If converter No. 2 were to be synchronized, plugs would be inserted at *a*, *b*, and *e*, thus connecting the upper terminals of the synchronizer to the bus-bars and the lower terminals to the corresponding phase of the converter. When the synchronizer is used on pressures somewhat above those for which it is made, it is necessary to insert resistances as shown at r_1 and r_2. In new installations, synchronoscopes are now used in preference to lamps.

APPARATUS FOR CONTROLLING THE OUTGOING CURRENT

30. The apparatus for the control of the outgoing current is generally grouped on a switchboard by itself. In most cases the current is delivered at comparatively low pressure; hence, the devices used on the switchboard for the outgoing current differ materially from those on the incoming lines. Generally, the delivered current is used for electric lighting and power, or street-railway purposes, and the switchboard appliances used are the same as if the power were supplied from an ordinary station. Rotary converters are operated in parallel and connected up on the direct-current side in exactly the same way as direct-current machines. If they are compound wound an equalizing connection must be used.

LOCATION AND GENERAL ARRANGEMENT OF SUBSTATIONS

31. One of the greatest advantages of the distribution of power by means of substations is that the substations may be placed at or near the centers where the heaviest demand for current exists. They do not have to be located with reference to coal or water supply, and the price of real estate becomes a comparatively small item, because substations have a very large output compared with the ground space they occupy. They can also be placed in locations

where a power plant would not be permitted on account of the smoke and dirt caused thereby. Substations can, for these reasons, be placed near the center of the load, and thus effect a great saving in the amount of copper required for feeders.

32. Fig. 34 shows the interior of a typical substation, one of the substations in Buffalo, N. Y., supplied with power from the Niagara power plant. All the machinery and controlling devices are here placed in one room, and a

FIG. 34

single attendant is all that is needed. It is a fireproof building provided with a hand-operated overhead traveling crane for handling the machinery during installation, or in case repairs are necessary. The step-down transformers *A*, *A* are ranged along one side, and the three rotary converters *B*, *B*, *B* along the other. Each converter is of 400 kilowatts capacity and is supplied by a group of three 150-kilowatt transformers, the secondaries of which are connected to the converter; air-blast reactance coils, placed

behind the transformers, are inserted between the transformers and the converter in order to permit voltage regulation by variation in field strength. The converters are six-pole machines supplied with 25-cycle current, and run at a speed of 500 revolutions per minute.

The incoming current at 10,000 volts enters in the basement by means of a lead-covered cable and passes through the hand-operated oil switch *C*, which is provided for cutting off all power from the station in case of emergency or for any other reason. From *C*, the current passes through the high-tension circuit-breakers located on the switchboard *D*, and provided with time-limit relays. After passing through the circuit-breakers, the current goes to the high-tension bus-bars *E* and from there to the three high-tension oil switches *F* mounted in a brickwork casing. In the figure, one of the iron covers is removed showing the three cells of one switch. Each switch controls the current in the primaries of a group of three transformers supplying a rotary converter. The potential transformers for supplying current to the voltmeters and synchronizing lamps are shown at *g*, *g* on top of the oil switches. The switchboard for controlling both the incoming and outgoing currents is shown at *H* immediately below the gallery containing the high-tension switches and circuit-breakers. The portion of the switchboard that contains the instruments for the alternating current is at the right-hand end at *K*; three panels are provided, one for each converter and group of three transformers. The switch handles for operating switches *F* are mounted on these panels and are thoroughly insulated, by insulating joints, from the switches themselves. The ammeters are supplied from current transformers, so that none of the appliances on the switchboard with which the operator might come in contact are exposed to the high pressure; all the high-pressure devices are confined to the upper gallery.

From the high-tension switches *F*, the current passes to the primary coils of the transformers and the induced current in the secondaries passes to the collector rings of the

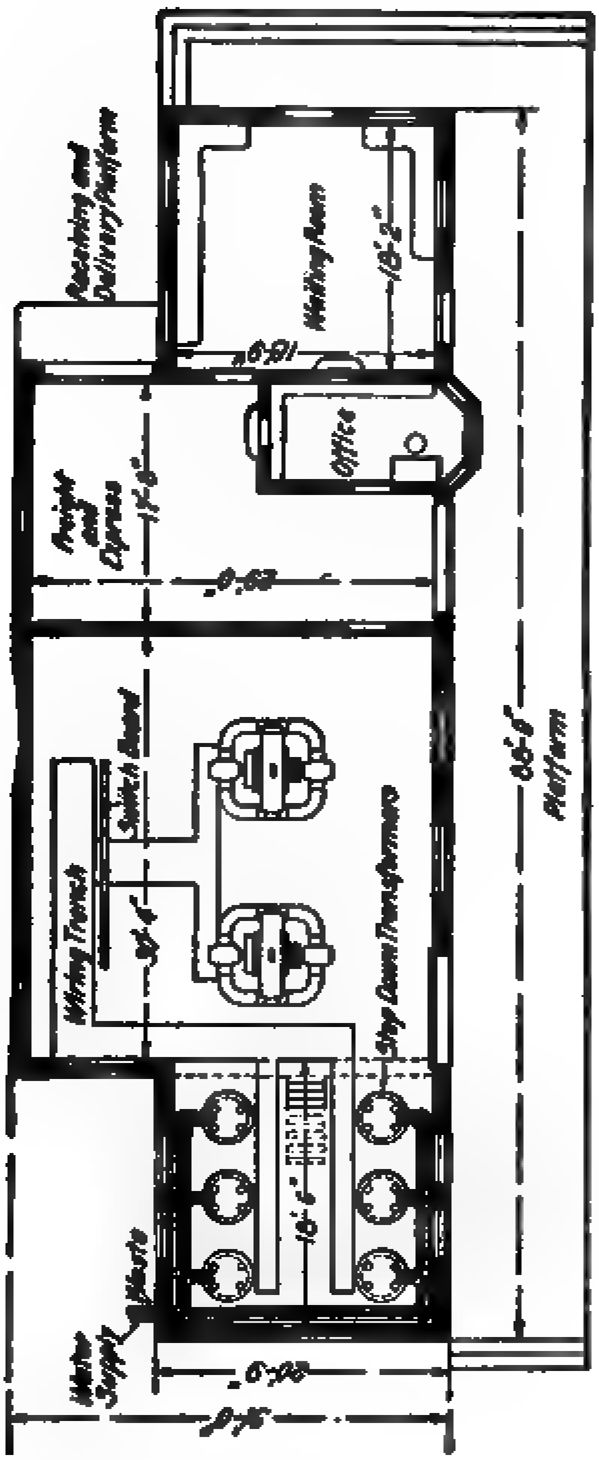

Receiving and Delivery Platform
Waiting Room
16'-2"
Office
Freight and Express
17'-6"
Switch Board
Wiring Trench
Step Down Transformers
Platform
Waste
Water Supply

FIG. 18

converters. The direct current passes to the panels *1*, *2*, *3*, each of which is provided with a direct-current ammeter and circuit-breaker in addition to the main switches. The outgoing feeders are connected to the feeder panels *4*, *5*, *6*, etc., each of which is provided with an ammeter, circuit-breaker, and main switch. Panel *9* carries an ammeter that measures the combined output of the converters, a voltmeter for measuring the direct-current voltage, and a recording wattmeter for registering the output of the substation. The voltmeter can be connected to any converter by means of plug connections on each converter panel. The subbase of each converter panel carries a single-pole switch for the field, and a double-pole transfer switch for connecting whichever converter is to be started to the starting switch on the subbase of panel *9*. Each converter is provided with an iron-clad magnet *m* mounted on the end of the bearing casing. A current is sent through this magnet at regular intervals, thus making the shaft oscillate back and forth and keeping the brushes from wearing ridges in the commutator. Mechanical devices that have the advantage of not requiring any current for their operation have also been designed for maintaining an oscillation of the shaft.

Fig. 35 shows the arrangement of a typical substation for an electric railway. The arrangement of the transformers, rotary converters, etc. is clearly shown, so that further comment is unnecessary.

CONNECTIONS FOR SUBSTATIONS

33. The connections used for the various appliances in a substation vary considerably in different installations, so that it is impossible to give any scheme that is generally applicable. For example, those for a substation supplying a street-railway system will differ from those for one supplying current for lighting purposes. In order to give an illustration of connections a few typical examples of substations for supplying direct current will be selected. In the first case the substation is to be supplied with current over one or

Incoming Lines

45B *Tendon*

Fig. 86

§26

both of a duplicate set of high-tension transmission lines. Two compound-wound rotary converters are used, which are to be arranged for parallel operation. The converters are to be started by means of direct current supplied by either one of the machines, it being assumed that one converter is always in operation. In case both were shut down for any cause, they could be started from the power station by starting up the alternator and bringing the converters and alternator up to speed together. Fig. 36 shows a scheme of connections that might be used for such a substation. It must be understood, however, that the connections in individual cases might differ considerably from those shown, and yet give practically the same results. The differences would not lie so much in the main connections as in those of the auxiliary parts, such as the various instruments, synchronizing devices, etc.

34. Path of Main Current.—The wiring, as a whole, can be divided into two sections; that between the converter *8* and the incoming lines *1*, *2*, and that between the converter and the outgoing feeders *20*, *20*. In the first section the current is alternating, while in the second it is direct. The main current enters on either one or both of the three-phase lines *1*, *2*, and passes to the high-tension bus-bars *3*, *3*. High-tension switches *1′ 2′* are provided to cut off all current from the station. From the bus-bars *3*, *3*, the high-tension current passes to the converters through the switches *4*, *4′*. We will confine our attention from this point to one converter, as the connections of each are exactly alike. After reaching switch *4*, the current passes through the high-tension fuses *5* to the primary coils of the step-down transformers *6*. The switch *4* is frequently provided with an automatic tripping device that will open the circuit in case of overload, in which case the fuses *5* are not needed. In other cases a non-automatic switch is used at *4*, and automatic circuit-breakers instead of fuses at *5*; the transformers *6* step-down the line voltage to an amount suitable for conversion. For example, in this case the

converters will supply a voltage of about 550 for street-railway purposes, and the voltage supplied by the secondaries of *6* will, for a three-phase converter, be $550 \times .612 = 337$ volts, approximately. From *6* the low-pressure alternating current passes through the reactance coils *7*, which are inserted to allow voltage regulation; in case potential regulators are used instead of reactance coils, they are inserted at this point. From *7*, the current passes to the collector rings of the converter *8* and is transformed to direct current at 550 volts. The direct current passes through the main switches *11, 11'* to the direct-current bus-bars *14*. Since this substation supplies an ordinary street railway operating with an overhead trolley or third rail, the negative bus-bar is connected to the track and ground, while the positive connects to the outgoing feeders, which in turn are attached to the trolley wire or third rail, as the case may be.

35. Connections for Synchronizing.—Each of the incoming lines is provided with a potential transformer t' or t'', and each converter is also provided with a high-tension transformer, such as t''' connected between the switch and the transformer primaries. In series with the secondaries of each transformer is a synchronizing lamp l_1, l_2, etc. Suppose that current is being supplied over line *1* and that converter *8* is to be synchronized. The converter is started, switch *4* being open, by supplying it with direct current. It generates an alternating current that is stepped-up by transformers *6* and supplies the primary of t''' with an alternating E. M. F. By inserting plugs at *a* and *c* the secondaries at t' and t''' are connected in series with each other and with lamps l and l_2. If one plug *c* is cross-connected, as indicated by the dotted lines, the lamps will be bright at synchronism. The synchronizing arrangement is essentially the same as that described in connection with the operation of alternators in parallel.

36. Voltmeter Connections.—In order to obtain a reading of the voltage on either incoming line, a voltmeter *V* is provided. By means of a voltmeter plug, connecting the

upper and lower terminals of either of the receptacles *e*, *f*, the voltmeter can be made to indicate the voltage on either line. The voltage of the high-tension side of either converter can be measured by means of the voltmeter *V'*, which is connected to the voltmeter receptacles *g*, *h*. The voltage of the direct-current side of the converters is indicated by the voltmeters *O*, *O'* connected to the voltmeter receptacles *p*, *p'*. The voltage of a converter can thus be compared with the voltage of the line or direct-current bus-bars to which it is to be connected.

37. Ammeter Connections.—Each converter is provided with an ammeter *I* connected to the secondary of a current transformer inserted between the switch *4* and the transformer primaries. In some cases an ammeter is inserted in each line wire, especially in large installations, though this is not absolutely necessary. In some cases, also, ammeters are placed on the incoming lines, series-transformers, of course, being used so as to thoroughly insulate the instruments from the high-tension line. The direct-current side of each converter is provided with an ammeter *21* connected across a shunt *12*. Ammeter *C* indicates the total direct current, since its shunt is connected in series with the main bus-bar between the converters and the feeders. The feeders are provided with feeder ammeters *i*, *i'* connected across the shunts *19*, *19'*.

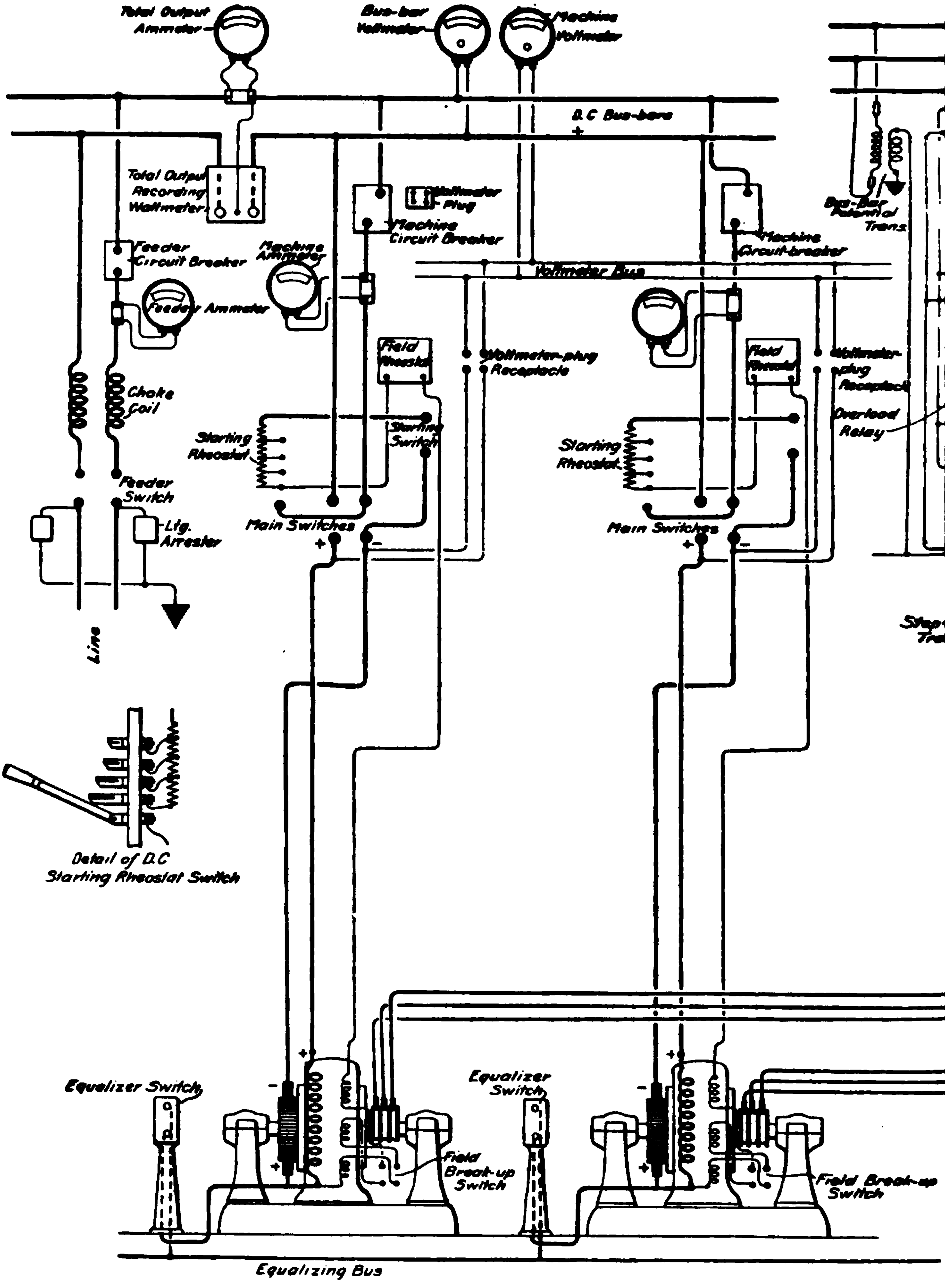
38. Circuit-Breakers.—In this case the incoming lines are not equipped with automatic circuit-breakers, though, if the substation formed part of a large network, circuit-breakers would likely be inserted at *k k'*, and these would be equipped with reverse-current and time-limit attachments. On the direct-current side each converter is provided with a circuit-breaker *13*, *13'* connected between the converter and the direct-current bus-bars. Each feeder is also provided with a circuit-breaker, as indicated at *18*, *18'*.

39. Equalizer Connection.—The positive brushes of the converters are connected by means of an equalizer cable in which the equalizer switch *15* is inserted. Note that

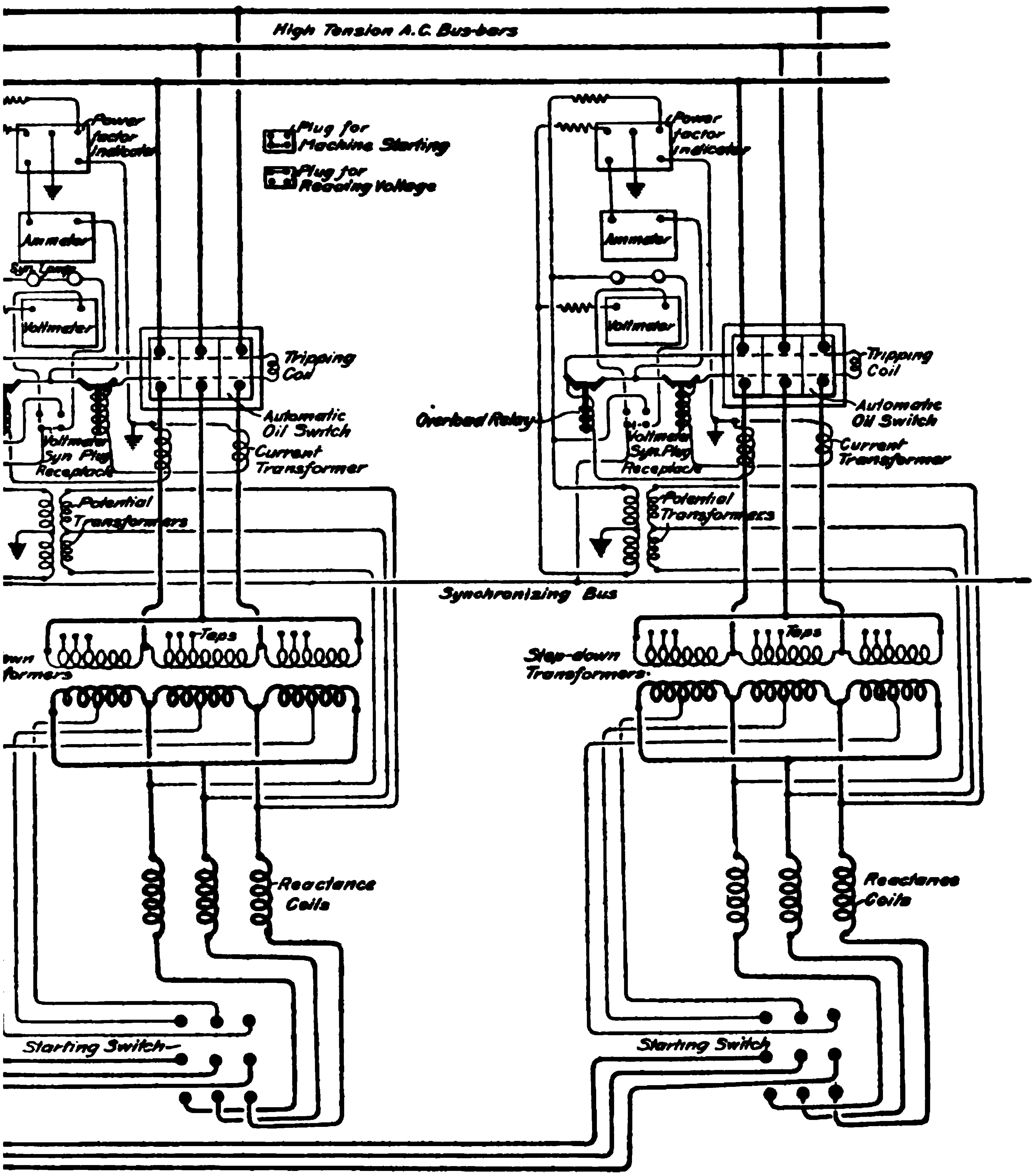
the equalizer connects the two brushes to which the series-field windings are attached.

40. Shunt-Field Connections.—One end of the shunt field connects to the + brush, and the other to one terminal of the field rheostat *R*. The other rheostat terminal connects to the blade of the field switch *m*. When switch *m* is moved to the right, thus cutting the current off from the shunt field, the pilot lamp l_4, resistance *r*, and rheostat *R* are connected across the field terminals, thus allowing the induced E. M. F., caused by the interruption of the field current, to discharge through this closed circuit. Switch *m* is in the position shown in the figure when the converter is in operation. Switch *n* allows the shunt field to be excited either from the direct-current bus-bars or from the converter itself. When it is partly closed, the blade makes contact with the long clip and the field is excited from the bus-bars; when fully closed, the field is connected across the brushes.

41. Method of Starting.—Suppose converter *8'* is in operation supplying current to the direct-current bus-bars, and that *8* is to be started and thrown in parallel with *8'*. Switches *4*, *11*, *11'*, *15*, *n*, and *m* are supposed to be open. Close the equalizer switch *15*; place field switch *m* in the position shown in the figure, and close switch *n* until the blade makes contact with the long clip. The shunt field will then be excited by current from *8'*, because one end of the field is connected through *R*, *m*, and *n* to the negative bus-bar, and the other end is connected to the positive side of *8'* through the equalizer. Close switch *11*, thus allowing current to flow through the series-coils *9*. The field is now fully excited and the converter can be started as a direct-current motor by allowing current to flow through its armature. This is done by throwing the switch *s* to the upper position and gradually closing the starting switch *S*. The speed of *8* can be adjusted by moving the field rheostat *R*, and when the point of synchronism is attained, as indicated by the synchronizing lamps, switch *4* is closed. After *S* has


Total Output Ammeter
Bus-bar Voltmeter
Machine Voltmeter
D.C Bus-bars
+
Total Output Recording Wattmeter
Voltmeter Plug
Machine Circuit Breaker
Feeder Circuit Breaker
Machine Ammeter
Feeder Ammeter
Voltmeter Bus
Machine Circuit-breaker
Bus-Bar Potential Trans.
Field Rheostat
Voltmeter-plug Receptacle
Choke Coil
Starting Rheostat
Starting Switch
Overload Relay
Feeder Switch
Ltg. Arrester
Main Switches
Line
Detail of D.C Starting Rheostat Switch
Equalizer Switch
Field Break-up Switch
Equalizing Bus

FIG



High Tension A.C. Bus-bars
Power factor Indicator
Plug for Machine Starting
Plug for Reading Voltage
Ammeter
Syn. Lamps
Voltmeter
Tripping Coil
Automatic Oil Switch
Overload Relay
Voltmeter Syn. Plug Receptacle
Current Transformer
Potential Transformers
Synchronizing Bus
Taps
Step-down Transformers
Reactance Coils
Starting Switch

been closed and the resistance cut out, switch *11'* should be closed and switches *S*, *s* opened; also, *n* should be fully closed, thus connecting the shunt field across the terminals of the converter and allowing the field to remain excited even if switches *11*, *11'*, and *15* are open. The transfer switch *s* is provided so that the starting rheostat *S* can be connected to either converter.

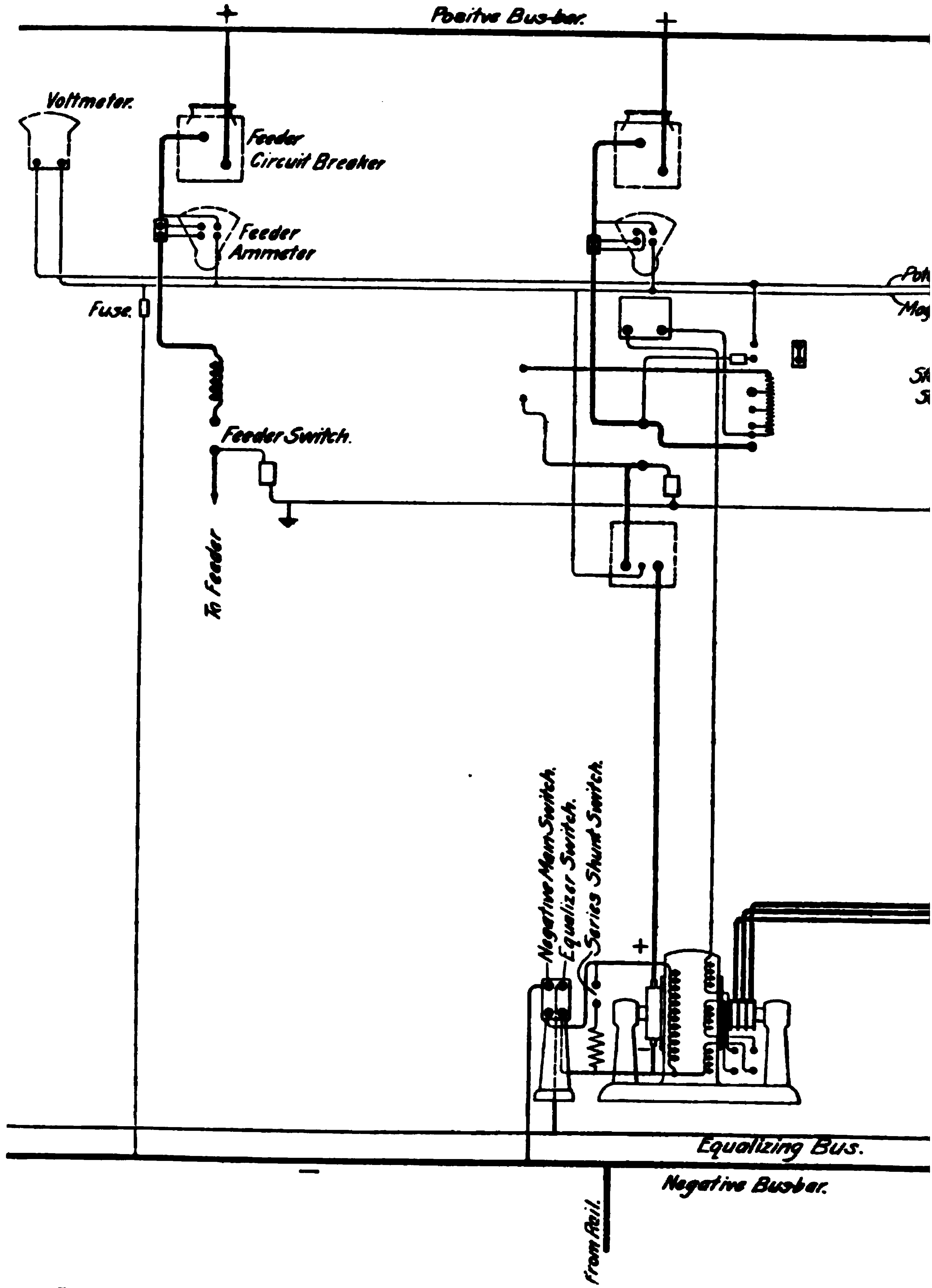
This method of starting from the direct-current side is sometimes modified as follows: The converter is speeded up as before and the field rheostat is adjusted so that the machine runs somewhat above synchronism. Then switches *11*, *11'*, and *n* are opened, thus cutting off the direct current and opening the field circuit. The converter is then running above synchronism under its own momentum, but is generating no E. M. F. Switch *4* is then closed and the converter is brought into synchronism by the alternating current, and as it is already running at nearly synchronous speed the amount of current required is not nearly as great as if the converter were started from rest by allowing alternating current to flow through the armature. The field circuit is then closed, the direct-current voltage adjusted, and the converter thrown in parallel on the direct-current side in the usual manner. This method of starting is sometimes advantageous when the load on the direct-current bus-bars is of a very fluctuating nature. The variations in voltage may under such circumstances make it difficult to synchronize with the lamps in the ordinary way.

In case the converters are started by means of an auxiliary induction motor mounted on the shaft, switches *S*, *s* are omitted and the necessary connections for the starting motor are provided instead.

42. Fig. 37 shows connections for a substation containing two rotary converters supplying current to a two-wire lighting or power system. The connections are, on the whole, very similar to those just described but differ from them in minor details. The switchboard is divided into two parts—the alternating-current board at the right and the

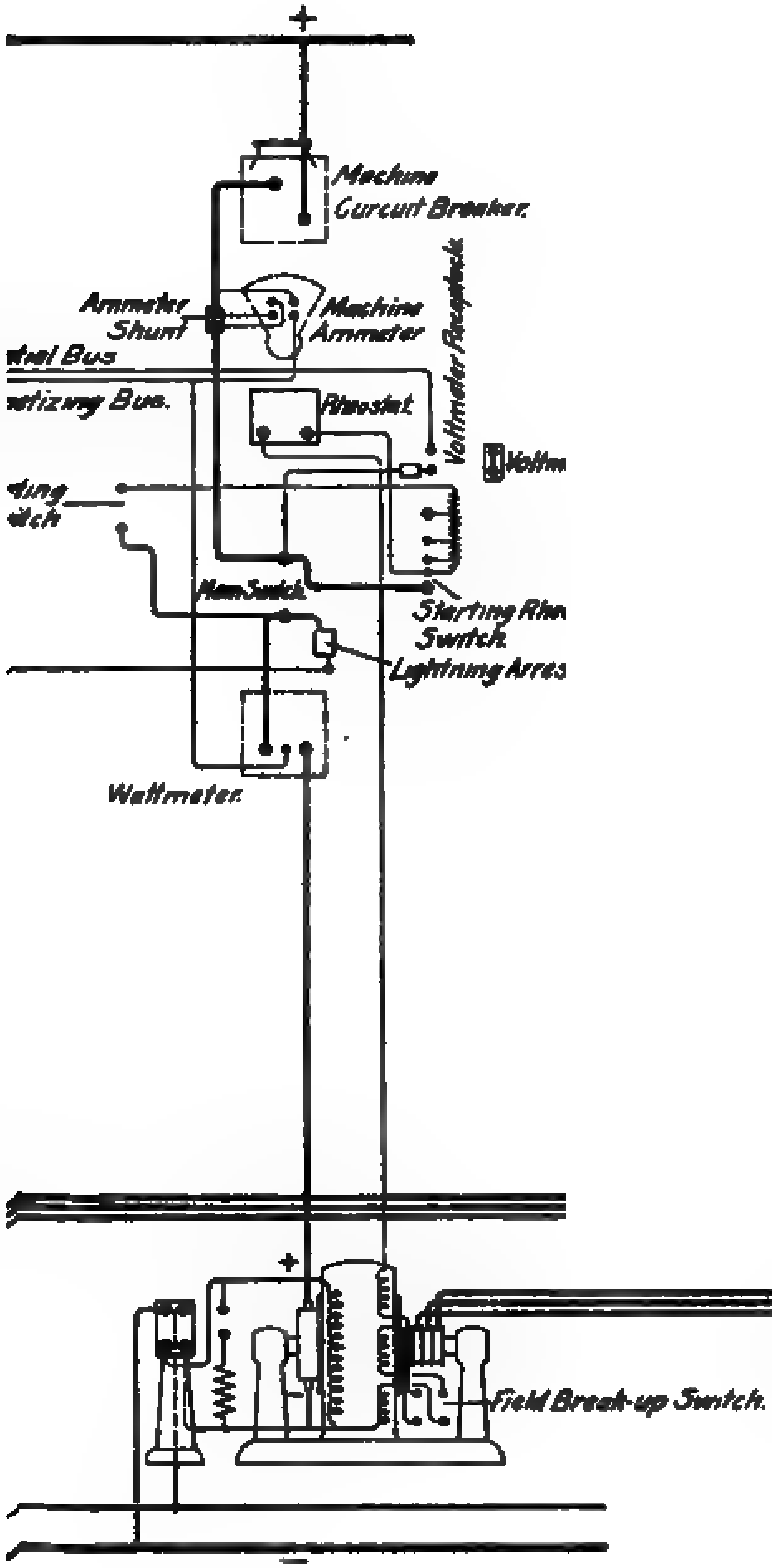
direct-current board at the left. The alternating-current board consists of two panels, each of which is equipped with a main switch, which may be located some distance from the panel but yet be operated therefrom; a voltmeter, ammeter, power-factor indicator, overload relays, synchronizing lamps, synchronizing plug, and potential, and current transformers. Each direct-current panel is equipped with two single-pole main switches, field rheostat, machine ammeter, circuit-breaker, voltmeter plug, and starting switch for starting from the direct-current side. Each feeder panel, of which one is shown in the figure, is equipped with a double-pole feeder switch, feeder ammeter, circuit-breaker, and lightning arrester. In addition to the instruments on the generator and feeder panels, a total output ammeter and a total output recording wattmeter are connected between the converters and feeders so as to measure the combined output of the machines. Also, two voltmeters are provided—one to indicate the bus-bar voltage and the other to indicate the voltage of the direct-current side of either converter. These instruments, together with the total output meters, are often mounted on a panel by themselves.

It will be noted in Fig. 37 that the connections are such that the converters can be started from either side. Each machine is provided with a double-throw starting switch on the alternating-current side by means of which the converter is supplied with a reduced voltage at starting. The primaries of the transformers are provided with a number of taps to adapt them to different line voltages, and reactance coils are inserted between the secondaries and the collector rings. The main switch is provided with an automatic tripping attachment that is operated by the overload relays. The synchronizing connections are such that either the synchronizing lamps or voltmeter may be used. Each converter is equipped with a power-factor indicator, which shows whether the current taken from the bus-bars is lagging or leading. The operation of this type of power-factor indicator will be explained later after polyphase meters have been taken up.


Positive Bus-bar.
+
+
Voltmeter.
Feeder Circuit Breaker
Feeder Ammeter
Fuse.
Feeder Switch.
To Feeder
Negative Main Switch.
Equalizer Switch.
Series Shunt Switch.
+
−
Equalizing Bus.
Negative Busbar.
−
From Rail.

45B

Fi


+
Machine
Circuit Breaker
Ammeter
Shunt
Machine
Ammeter
Voltmeter Receptacle
Rheostat
Starting Rhe
Switch
Lightning Arres
Wattmeter
+
Field Break-up Switch.
—

43. The method of starting from the direct-current side is briefly as follows: On the alternating-current side, the starting switch is thrown to the lower position and the main oil switch is open. The field break-up switch and the equalizer switch at the machine are also closed. The break-up switch is used only when the converter is started from the alternating-current side. The + main switch, the circuit-breaker, and the single-pole starting switch are then closed, first making sure that the starting rheostat switch is open. Closing the + main switch and the equalizer switch places the series-coils in parallel with the series-coils of the converter that is already in operation and also connects one end of the shunt-field winding to the + side of the system. As soon as the starting rheostat switch is placed on the first point, current flows through the armature and shunt field. The converter then starts as a direct-current motor and comes up to speed as the starting rheostat switch is pushed in. After this switch has been fully closed, the − main switch is closed and the rheostat switch opened. The converter is now synchronized by varying the field strength, and when the lamps or voltmeter indicate synchronism the oil switch is closed.

When a converter is started from the alternating-current side, the switches on the direct-current side are open and the field break-up switch is also open. The double-throw starting switch is thrown to the upper position and the main oil switch closed. When the machine has attained speed, the starting switch is thrown over to the full-voltage position. The field is then excited and, after making sure that the polarity of the direct-current side is correct as indicated by the direct-current voltmeter, the converter is thrown in parallel on the direct-current bus-bars.

44. Fig. 38 is a diagram of connections similar to Fig. 37 except that, since the direct current is delivered to a railway system, the arrangement of the apparatus on the direct-current side is different. The connections on the alternating-current side are shown for one converter only; they are the

same as in Fig. 37. The negative bus-bar is placed near the machines instead of on the direct-current switchboard, and the negative main switch is placed alongside the equalizer switch, the converters being equalized on the negative side. The negative bus-bar is connected directly to the rail or return circuit, so that the direct-current panels are single-pole and the connections thereby simplified. The arrangement shown in Fig. 38 is used by the General Electric Company and the direct-current ammeters are of the Thomson astatic type, in which the magnetic field is supplied by electromagnets excited from the bus-bars. Each ammeter has a pair of wires to supply the exciting current in addition to the usual pair connecting to the ammeter shunt. The series-field of each converter is provided with a shunt to regulate the amount of compounding; this shunt can be cut out by means of the switch shown in the figure. This is necessary when starting from the alternating-current side; otherwise, the alternating E. M. F. induced in the series-coils would set up a large current through the shunt. These diagrams give a general idea of the connections used for substations, but it must be remembered that they admit of considerable variation and must be adapted to the requirements of each particular case. It is not possible therefore to lay down any general scheme that is applicable to all cases.

MEASUREMENT OF POWER ON POLYPHASE CIRCUITS

INSTRUMENTS USED FOR POWER MEASUREMENT

45. Reference has already been made, in connection with alternating currents, to the measurement of power on alternating-current circuits. The measurements there described related to simple single-phase circuits; the influence of the power factor on the actual power delivered was pointed out, and the use of the wattmeter was explained. As the applications of polyphase currents to power transmission have now been described, it will be advisable to consider the methods available for measuring the power supplied to two-phase and three-phase systems.

46. On account of the fact that the power factor of alternating-current circuits, either single-phase or polyphase, is seldom 100 per cent. or unity, power measurements are seldom made with ammeters and voltmeters as in direct-current work. The three ammeter and three voltmeter methods are inconvenient, liable to considerable error, and are never used if wattmeters are available. Good portable wattmeters are now obtainable at a price but little greater than that of ammeters or voltmeters. The wattmeter does not indicate the product of the volts and amperes, but the product, volts $\times$ amperes $\times$ cos ϕ, where cos ϕ is the power factor.

In making practical power measurements we may wish to obtain simply a reading of the total watts supplied at any given time or we may wish to obtain the total work done, in watt-hours or kilowatt-hours, during a certain period of time. In the first case, indicating wattmeters would be used to make the measurements, while in the second it would be necessary to use recording wattmeters, or watt-hour meters, as they should more properly be called.

INDICATING WATTMETERS

47. The **indicating wattmeters** used for power measurement on polyphase circuits are in nowise different from those already described for use on single-phase circuits. Many reliable makes of portable wattmeters are now available and these are used for commercial measurements. The number of wattmeters required for a given test depends on the conditions under which the test is made. In some cases one wattmeter is sufficient; in others, two are necessary, as will be shown. In connection with polyphase measurements, it is well to bear in mind the fact that if the difference in phase between the currents in the two coils of a Siemens type of wattmeter becomes more than 90°, the twisting action on the movable coil reverses, and, hence the deflection reverses. In ordinary single-phase circuits this condition does not arise, but it is possible in certain cases to have a greater phase difference than 90° on three-phase circuits, and the negative deflection referred to above must be taken into account.

RECORDING WATTMETERS

48. The **Thomson recording wattmeter** has been described; it operates on either direct or alternating current and can be used for measurements on polyphase or single-phase circuits. Meters of the induction type, having no commutator, are simpler in construction than the commutator meter, and have rapidly come into favor. They, of course, have the disadvantage that they cannot be used on direct current, whereas the Thomson meter can be used on either direct or alternating, a considerable advantage where a company supplies both kinds of current. Also, induction meters must be used on circuits having the frequency for which they are adjusted; if used on circuits of other frequency their indications will be incorrect.

49. **Induction wattmeters** are made in many different forms, but they all operate on about the same principle.

They are essentially small induction motors designed to operate with single-phase or polyphase current. Figs. 39 and 40 illustrate the operation of this class of recording meter, though it will be understood that it is possible to have a different arrangement of the parts and yet have the meter operate equally well. In Fig. 39, *a* is a coil of fine wire wound on the laminated iron core *b*; *c*, *c* are coils of a few turns wound on a core *d*, which is entirely separate from *b*. An aluminum disk *e* is mounted on the shaft *f* so that the outer part of the disk revolves past the ends of the cores on which the coils are wound. Fig. 40 shows a section of the coils and core taken along the line *fg*. Coils *c*, *c* are connected in series with each other and with the circuit so that all the current supplied passes through them. The potential coil *a* is connected across the circuit so that the current in it is proportional to the voltage; *c* and *a* therefore correspond to the current and potential coils of an ordinary wattmeter. The magnetism set up in core *b* will be proportional to the voltage, and that set up in core *d* will be proportional to the current. Coil *a* has a high inductance and an additional inductance is usually connected in series with it; in any event,

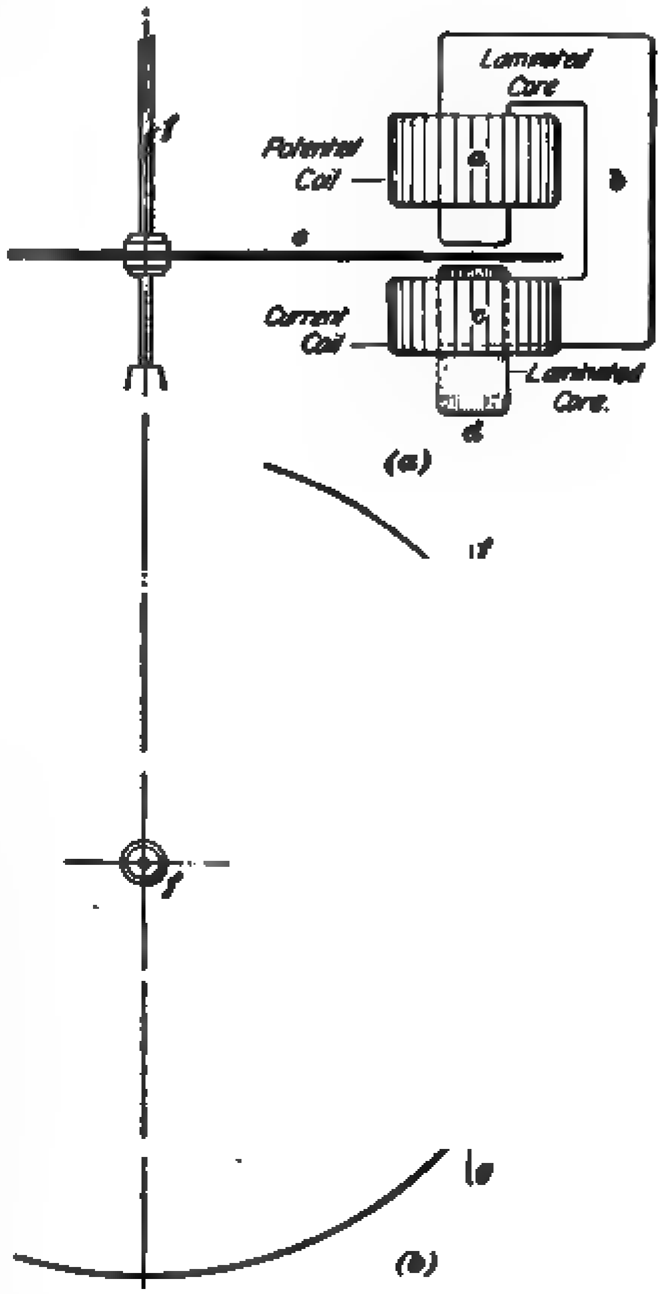


Fig. 39

the meter is so designed that the current in coil *a* will lag approximately 90° behind the E. M. F., thus making the magnetism in *b* lag 90° behind the E. M. F. The current in coils *c*, *c* is, of course, in phase with the current supplied to the circuit in which the meter is connected. The alternating magnetic field set up, say, by coil *a* induces eddy currents in the disk, which spread out somewhat as indicated by the dotted lines *o*, Fig. 39 (*b*). These currents are reacted on by the field that emanates from the poles of core *d* and the disk is made to rotate.

In order that the meter shall give an accurate indication of the work done in the circuit, the driving torque on the disk must be proportional to $EI \cos \phi$, where $\cos \phi$ is the power factor of the circuit. Let us first consider the case where the power factor is 1, i. e., where the line current and line E. M. F. are in phase. The current in *a* is at right angles to the line E. M. F. and the induced eddy currents in the disk are at right angles to the magnetic flux, because these currents depend on the rate of change of the flux, and the flux is changing most rapidly when the magnetizing current is passing through zero. The magnetism in *d* is in phase with the current; hence, for the power factor of 1, the currents in the disk are in phase with the magnetism set up by the series-coils; consequently, the driving torque is a maximum for the given values of the line current and E. M. F. Suppose that we have the same current and E. M. F. but that the power factor is less than 1. The line current will lag behind the E. M. F., the magnetism in *d* will not reach its maximum at the same instant as the currents in the disk, and the driving torque will be reduced, thus making the meter run slower. A magnetic brake is provided by making the disk revolve between the poles of permanent magnets in the same manner as in the Thomson meter. This makes the speed at

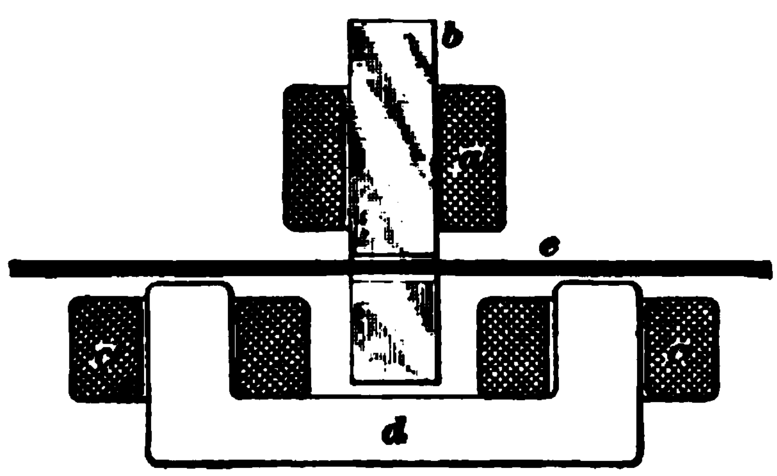


FIG. 40

all times proportional to the driving torque. If it were possible for the circuit to have a power factor of zero, i. e., if the line current lagged 90° behind the E. M. F., the torque action on the disk would be zero, because the induced currents would be at right angles to the magnetism in *d*. In other words, when the currents in the disk were a maximum there would be no field for them to react on, and when the field magnetism was at its maximum there would be no currents in the disk. The meter would not therefore record any power even though current would be flowing in coils *a*, *c*. This is

Fig. 41

as it should be, because with zero power factor, the watts supplied would be zero no matter what the values of the current and E. M. F. might be. The induction meter can therefore be made to record the number of true watts expended in a circuit no matter what value the power factor may have.

50. Fort Wayne Induction Wattmeter.—Fig. 41 shows a Fort Wayne single-phase induction wattmeter. *D* is the armature, which, in this meter, takes the form of an inverted aluminum cup. *E* is the damping magnet that exerts a drag on the armature and makes its speed proportional to the driving torque. The current and potential

coils are at the back of the armature; *a* is one current coil, and the other coil occupies a similar position on the opposite side of the armature. The speed of the meter can be adjusted by shifting the magnet *E* up or down, thus varying the amount of the armature embraced by the pole pieces of the permanent magnet.

51. Stanley Induction Wattmeter.—In the Stanley recording wattmeter the armature is an aluminum disk acted on by current and potential coils in much the same manner as previously described. The most interesting feature of this meter is the method of suspending the disk. Instead of resting on a pivot, as in most meters, the disk *a*, Fig. 42, is suspended magnetically. It is mounted on a small, hollow, steel shaft *b* through which passes a fine steel wire *c* stretched taut by means of the screw *d* and spring *e*. The shaft *b* has in it two small brass bushings, one at each end, that bear against the wire and keep the disk from tipping sidewise, otherwise the disk has no support. A permanent magnet *f* is provided with pole pieces *g*, *h* shaped as shown; *k* is a brass plug. From the way in which the pole pieces are shaped the lines of force passing across the gap at *l* hold the shaft in a central position between the poles so that the shaft and disk are magnetically suspended and revolve with very little friction. The reduction in the friction makes the meter more accurate, particularly on light loads, and there is no pivot to be damaged by shock or vibration. The recording dial is operated by gears driven from the shaft by the teeth shown at *m*.

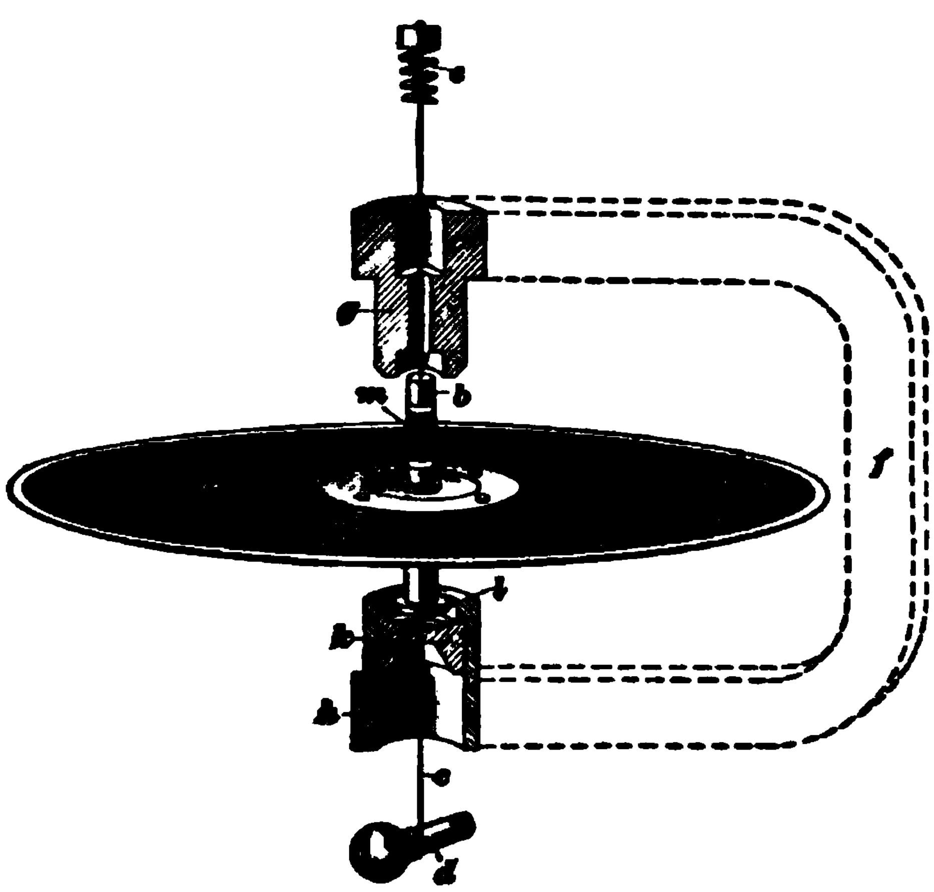


Fig. 42

MEASUREMENT OF POWER ON TWO-PHASE CIRCUITS

52. In making power measurements on polyphase circuits, the methods used will depend, to some extent, on whether the load on the system is balanced or not. The load in such a system is said to be *balanced* when the current in each of the phases is alike, and the power factor of the load on each phase also alike. In other words, the loads on the different phases of a balanced system are alike in every particular; under such circumstances it would be accurate enough to simply measure the power delivered to one phase and multiply the result by the number of phases. Unfortunately, an exact balance is seldom realized in practice,

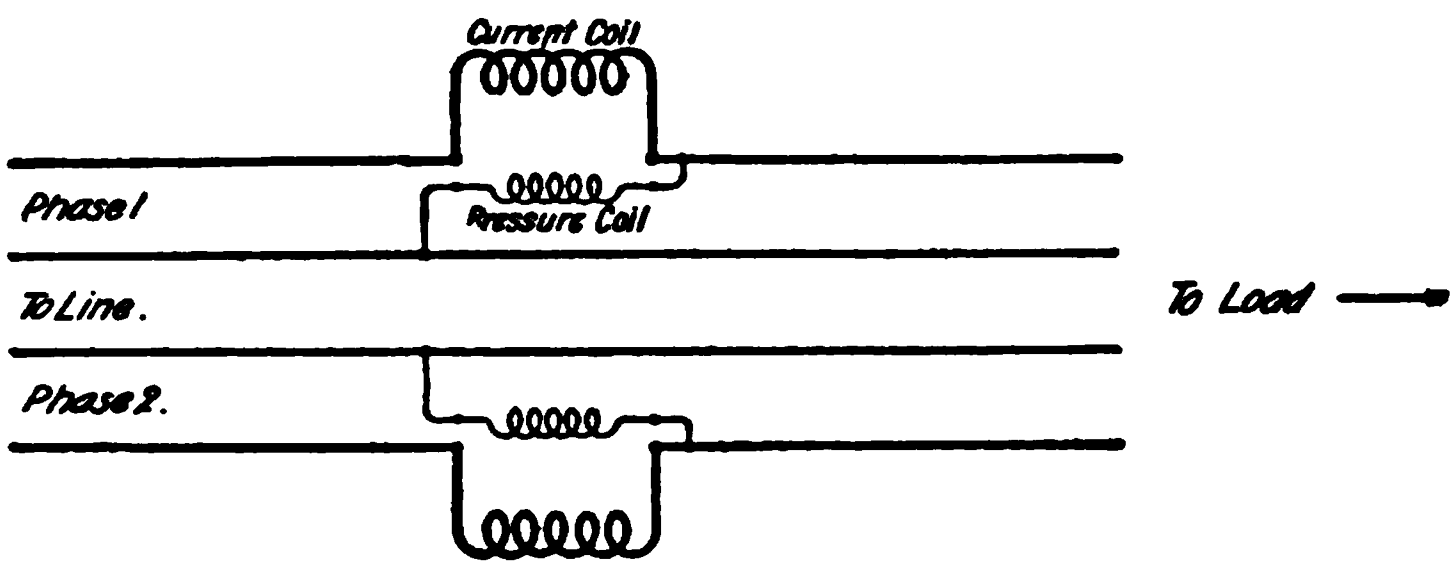


FIG. 43

although induction motors, synchronous motors, and rotary converters in themselves constitute a nearly balanced load, because they take current from the different phases in practically equal amounts. When a mixed load of lights and motors is operated, it is almost impossible to obtain an exact balance.

53. Two-Phase, Four-Wire System.—Fig. 43 shows the usual method of connecting wattmeters for measuring power on a two-phase, four-wire system. Each phase is provided with a wattmeter, there being a current coil in each phase; the pressure coils are connected across the phases. In series with the pressure coil there would be a resistance, as in all wattmeters of the electrodynamometer type; this

resistance is not shown in the accompanying figures, and the fine-wire coil can be taken to represent the complete potential circuit of the wattmeter including the usual protective resistance.

Fig. 43 shows two distinct circuits containing wattmeters. It is evident that the sum of the two readings will give the total power supplied to the motor or other devices to which the lines are connected. Also, the sum of the readings will give the power supplied whether the load is unbalanced or not, because each wattmeter measures the actual number of watts supplied to the phase in which it is connected. Fig. 44 shows the two wattmeters used on a two-phase system with a common return. Recording wattmeters of

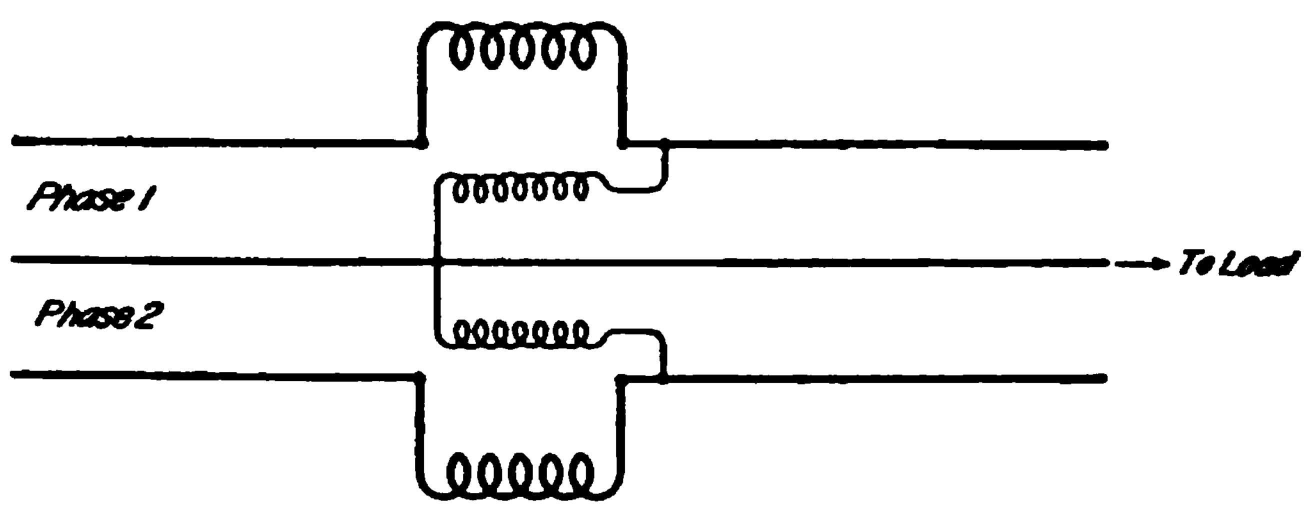


FIG. 44

the induction type are made, in which two sets of series-coils and two potential coils act on a common armature, thus practically combining two single-phase meters into a single meter, so that only one instrument is required to measure the energy no matter what the power factor may be or how unbalanced the current in the two phases.

54. Induction Wattmeter for Unbalanced Polyphase Circuits.—Fig. 45 shows a General Electric polyphase meter of the induction type for measuring energy supplied to unbalanced two-phase, three-phase, or monocyclic circuits. It operates on exactly the same principle as the single-phase induction wattmeter and is essentially two sets of single-phase meter coils acting on a common disk armature *a*. The two potential coils *b*, *b* are shown above the disk; they are connected in series with the reactance

coils *c*, *c*. There are four current coils, two of which are shown at *d*, *d*. A pair of current coils is situated under each potential coil and current is supplied to the front pair by means of the conducting strips *e*, *e*. The ends of the series-coils connect to terminals *f*, *f*, *g*, *g*, to which the mains are connected; *h* is one of the two magnets that retard the disk. Each set of coils *b*, *d*, *d* constitutes a single-phase induction meter, and as both these act on the same disk *a*, it follows that the resultant effort that turns

FIG. 45

the disk is a combination of the efforts exerted by the two sets of coils, and the record given by the meter is, therefore, a true indication of the watts supplied. In Fig. 45, one set of series-coils *d*, *d* would be connected in series with phase *1*, and the other set in series with phase *2*. The potential coils *b*, *b* would be connected across the two phases. In a three-phase circuit the two sets of series-coils would be connected in series with the two outside wires, and the potential coils would be connected between the outside wires and the middle wire.

55. The Use of a Single Wattmeter on a Two-Phase Circuit.—In Figs. 46 and 47 are shown methods of measuring the power on a two-phase circuit with a single wattmeter; these can be used in case the load is balanced. In Fig. 46, the current coil is connected in the common return wire, and a reading is first taken with the potential coil connected across phase 2, as shown by the full line. The connection *a* is then transferred to *a'*, thus connecting the potential coil across the other phase. The sum of the two

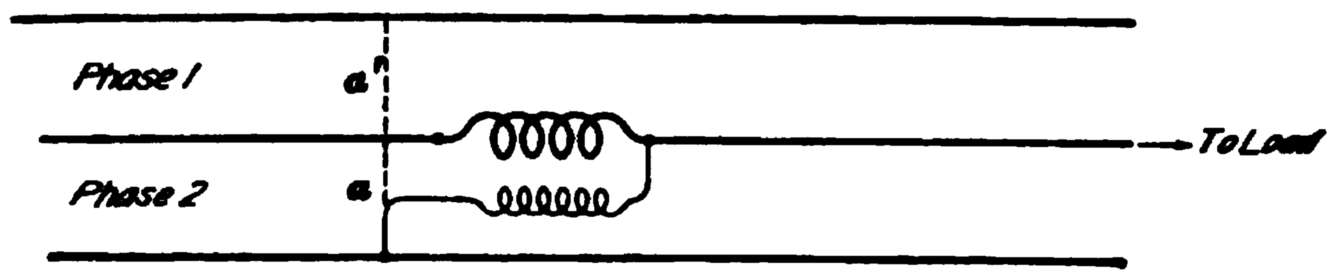


FIG. 46

readings gives the total power supplied no matter what the power factor of the load may be. In Fig. 47 (*a*), two series transformers and one shunt transformer are shown. The secondary coils of the series transformers are so connected that the current in the wattmeter series-coil will be the difference of the currents in the two transformer secondary coils. The E. M. F. impressed on the shunt coil of the wattmeter is proportional to the difference between the E. M. F.'s of the two

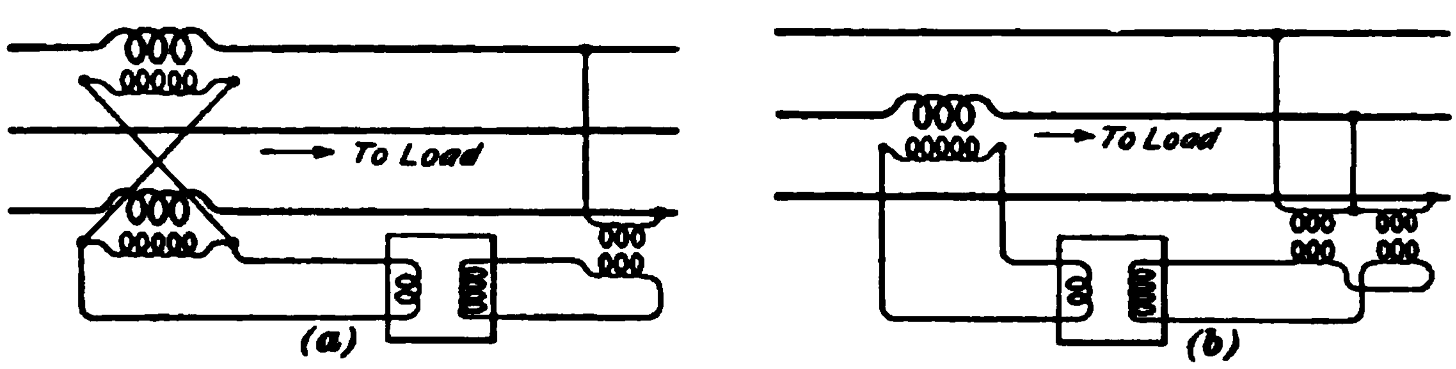


FIG. 47

phases. The resultant current and the resultant E. M. F. are thus in phase, and the single wattmeter measures the power on the two-phase circuit. In Fig. 47 (*b*), the connections of the secondary coil of one of the shunt transformers are reversed. The E. M. F. impressed on the shunt coil of the wattmeter is proportional to the sum of the E. M. F.'s of the two phases. The current in the series-coil of the wattmeter is also proportional to the sum of the two line currents.

That is, a single wattmeter connected as shown in Fig. 47 indicates the total number of watts supplied provided the load is balanced. These methods of using a single wattmeter are convenient, but it is always best to use the two wattmeters if they can be obtained, because one cannot always be certain that the load is balanced.

MEASUREMENT OF POWER ON THREE-PHASE CIRCUITS

56. Power may be measured on a three-phase circuit by using one, two, or three wattmeters. Two-wattmeter measurements are the most common, as the use of a single wattmeter requires either that the load be exactly balanced, or that the connections be transferred from one phase to another and the load kept constant during the change.

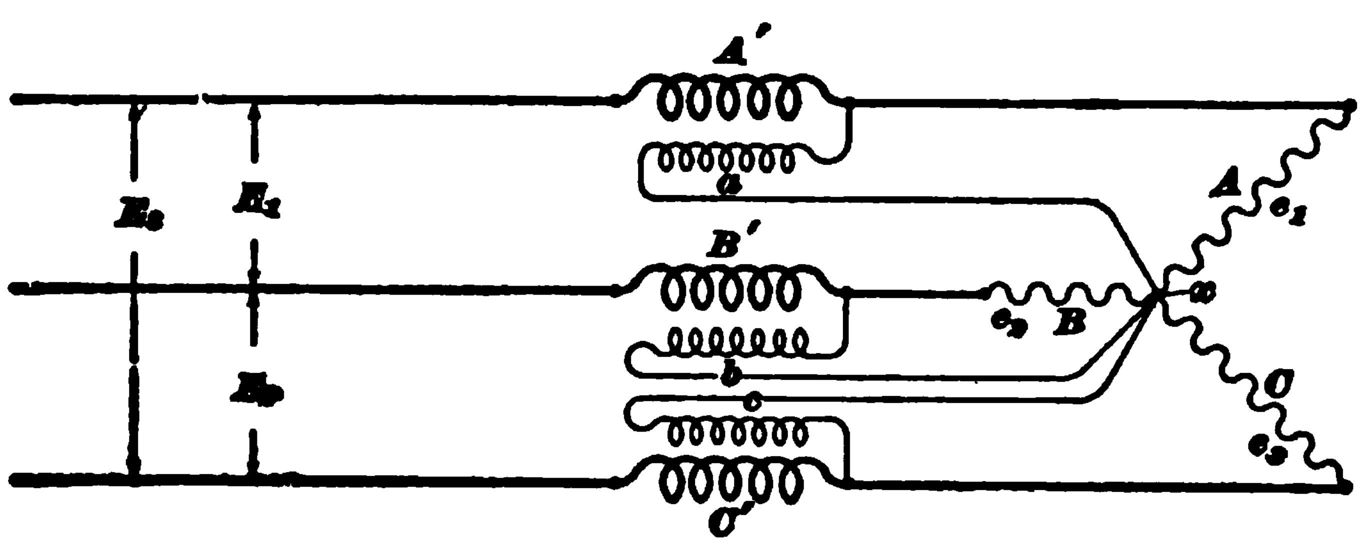


FIG. 48

57. Use of Three Wattmeters.—Let *A B C*, Fig. 48, represent the three windings of a Y-connected three-phase alternator. In a balanced system, e_1, e_2, and e_3 being equal, the line E. M. F.'s E_1, E_2, E_3 are also equal, and are equal to the E. M. F. in one winding multiplied by $\sqrt{3}$. The current in each line will be the same as the current in the winding to which it is connected, and in a balanced system the three currents will be equal. Three wattmeters with their current coils *A' B' C'* connected in the lines and their potential coils *a b c* connected across the corresponding winding, will measure the power delivered no matter whether the load be balanced or unbalanced, inductive or non-inductive.

It is evident from the way in which the wattmeters are connected that the potential applied to the pressure coil is equal to that generated in the winding with which the current coil is in series. Hence, the reading of wattmeter A' will be $e_1\, i_1 \cos \phi$, where ϕ is the angle of lag between the current and E. M. F. The other two meters will give the power developed in phases B, C, and the sum of the three readings gives the total power. If the load were exactly balanced it would be necessary to use but one wattmeter and multiply its reading by 3 to obtain the total power. In case $A\ B\ C$ represented the windings of an induction motor, synchronous motor, transformers, or in fact a load of any kind, this method of measuring the power could

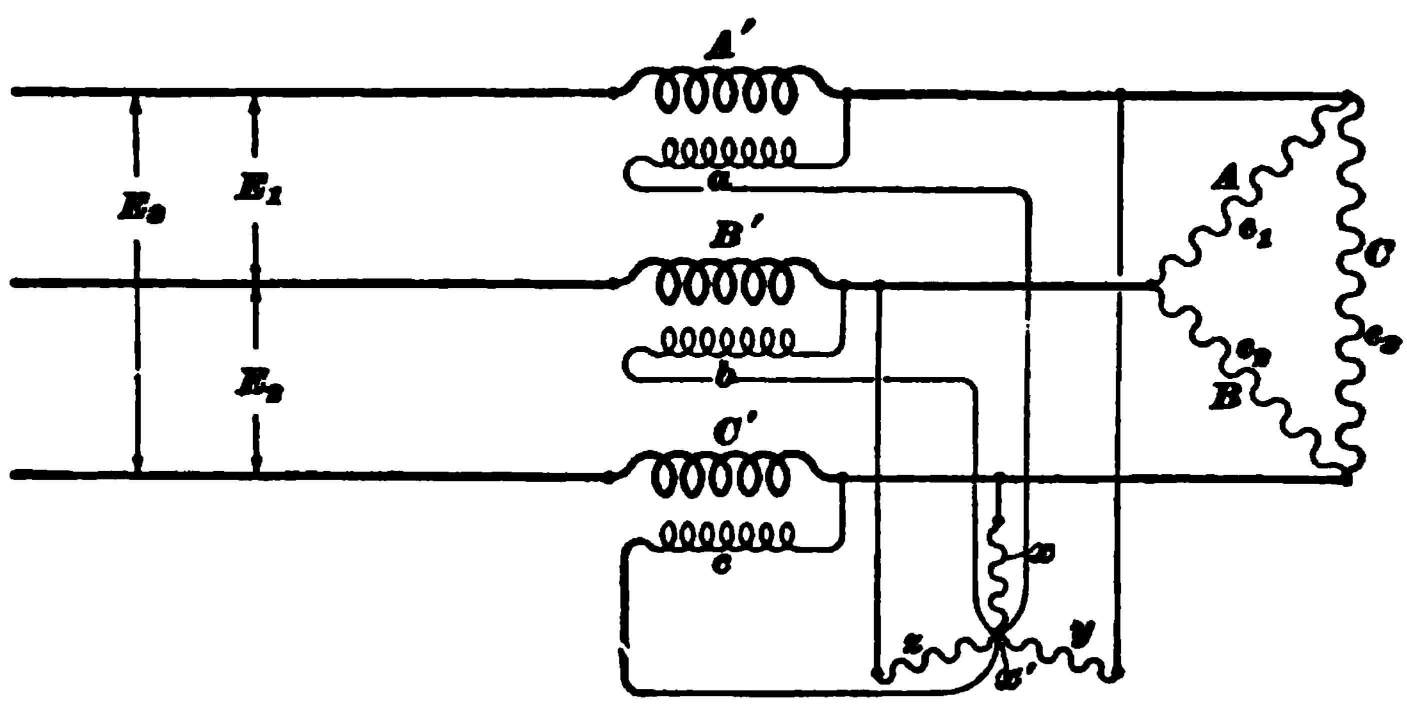


FIG. 49

be applied, though, as shown later, it is possible to measure an unbalanced three-phase load with two meters, and the three-meter method is therefore little used.

In most cases it is not possible to get at the neutral point x, Fig. 48, to connect the potential coils. In such cases an artificial neutral point may be obtained, as shown in Fig. 49, by connecting three non-inductive resistances x, y, z across the three phases, and attaching their neutral point x' to the potential coils. These resistances might be made up of wire wound non-inductively, or of incandescent lamps. The sum of the three wattmeter readings would then give the total power supplied as before.

58. Use of Single Wattmeter With Y Resistance. If the load were balanced, it would be sufficient in Fig. 49 to use but one wattmeter and multiply its reading by 3.

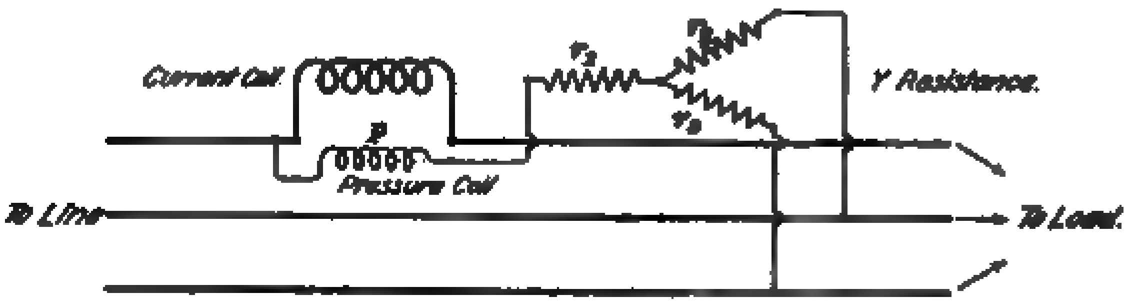


Fig. 50

Fig. 50 shows the connections for a single wattmeter used in this way. The resistances r_1, r_3 correspond to resistances x, z. Resistance r_2 is the usual protective resistance in series with the movable wattmeter coil. Fig. 51 shows a Thomson recording wattmeter with Y resistance; a is the starting coil of the wattmeter intended to compensate for the friction and to secure more accurate readings on light loads. By comparing Figs. 50 and 51 it will be seen that the connections are identical, the recording meter being connected in exactly the same way as the indicating instrument. Fig. 52 shows the connections of a recording meter on a three-phase balanced circuit where the pressure is over 500 volts; the potential circuit is here supplied through the small step-down transformers t, t. For very

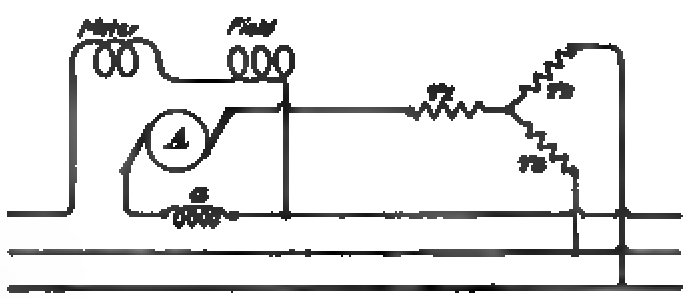


Fig. 51

high-pressure circuits, the current coils would be connected to the secondaries of current transformers instead of directly in the circuit. Fig. 53 shows the connections of a Wagner indicating wattmeter for measuring the power on a balanced three-phase circuit. The stationary current coils *A*, *A* are connected in series with the secondary of a current transformer *C* instead of being placed directly in the circuit. The movable potential coil *B* is supplied with current from the small transformers *D*, *D*. A Y resistance is used, the two branches being in the separate cage *E*; the protective resistance *F* is used to limit the current in the potential coil.

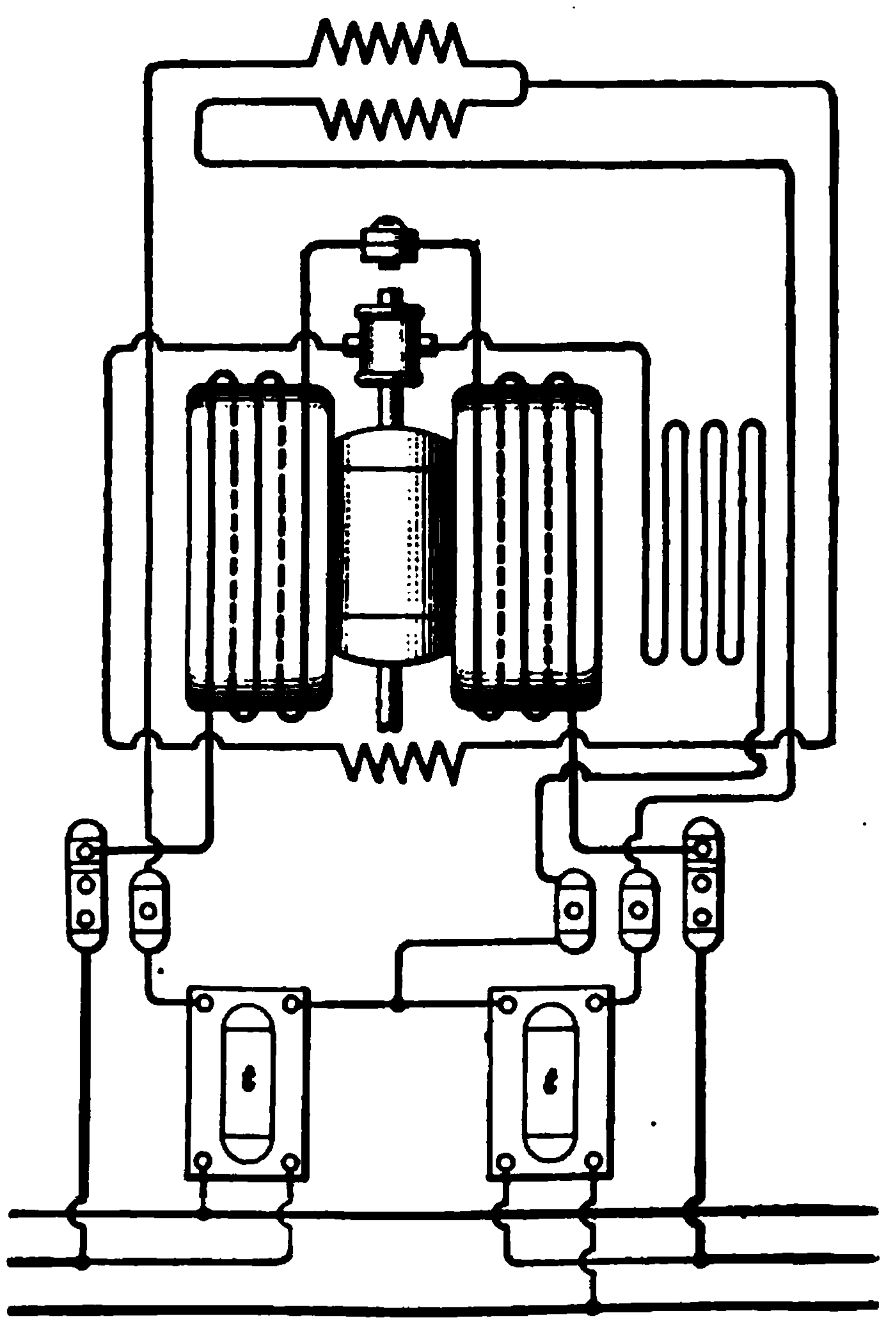


FIG. 52

59. Use of Two Wattmeters on Three-Phase Circuits.—The most common method of measuring the power supplied to a three-phase circuit is by means of two wattmeters connected as shown in Fig. 54. The current coils *A*, *B* are connected in two of the lines, and the potential coils between these two lines and the third line. If the power factor of the load is over .5, i. e., if the angle of lag is less than 60°, the sum of the two wattmeter readings gives the power supplied. If the power factor is less than .5, i. e., if the angle of lag is greater than 60°, the difference of the readings gives the power.

Since the coil *A*, Fig. 54, is connected in one line and the potential coil *a* between the outside and middle lines, it is evident that even on a non-inductive load the current in *A* is not in phase with the current in *a*. On a non-inductive load

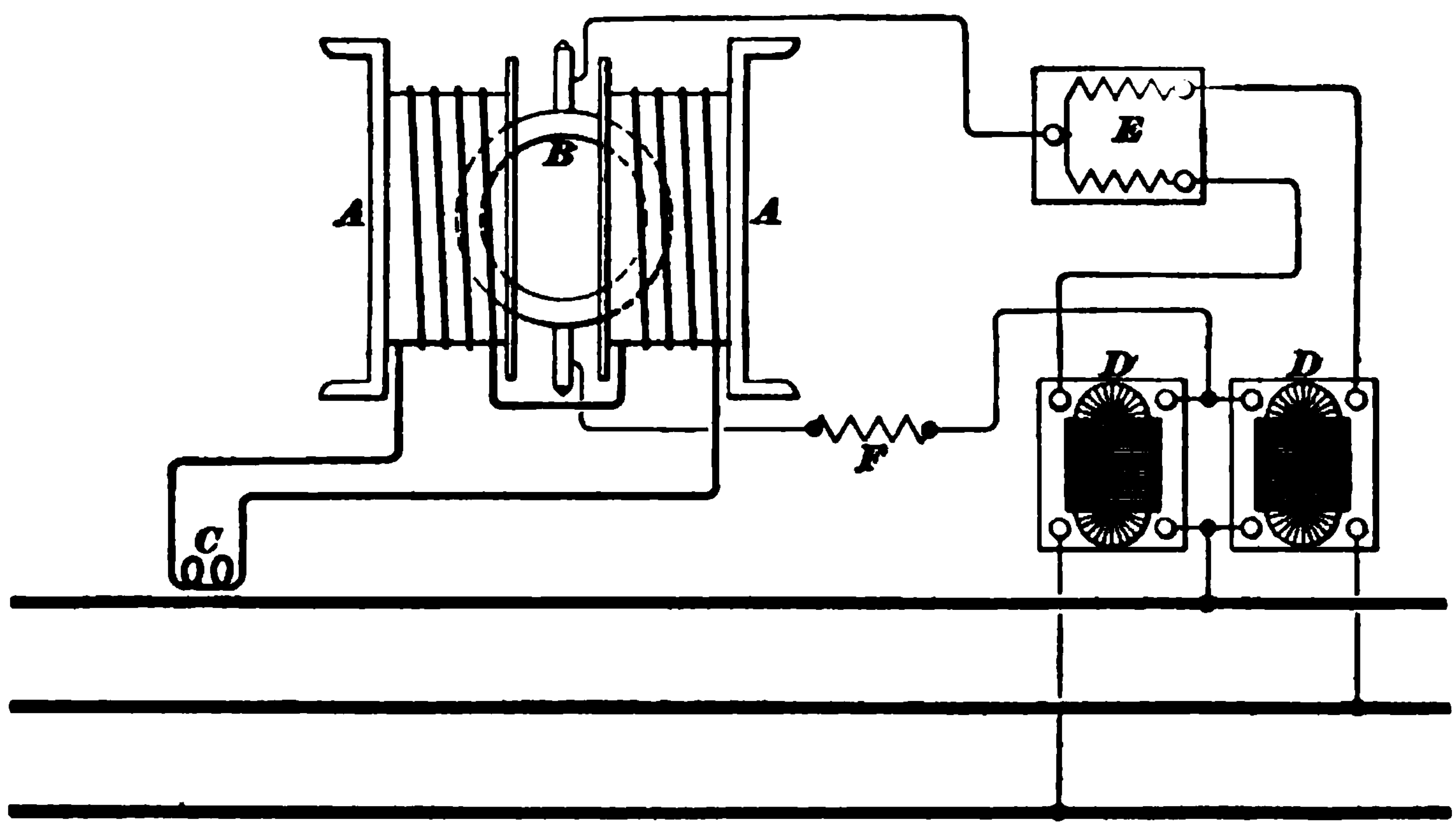


FIG. 53

the current in *A* will differ in phase from the E. M. F. between *1* and *2* by 30°, and the current in *B* will differ in phase from the E. M. F. between *2* and *3* by 30°. In Fig. 55, suppose that *x* represents the neutral point of the system, and that the lines *x–1′*, *x–2′*, *x–3′* represent the three voltages, differing

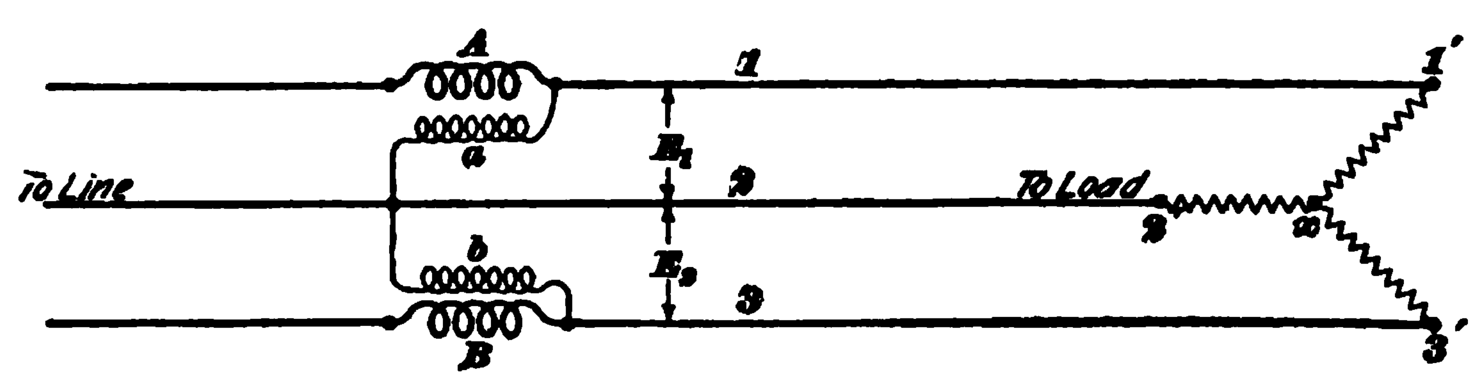


FIG. 54

in phase by 120°. Then the voltage between lines *1* and *2* is equal to *1′–x* plus *2′–x*, and is found by producing *x–2′* backwards and finding the resultant *x–4*. This resultant is 30° behind the voltage *x–1′*. The voltage between lines

2 and *3* is *x–5′* found by producing *x–3′* backwards and combining with *x–2′*. Since the wattmeters are connected symmetrically, as in Fig. 54, we must consider the E. M. F. acting on coil *b* as the E. M. F. taken in the direction *3–2* or *3′–2′* instead of *2′–3′*, since we have taken the other E. M. F. in the direction *1–2* or *1′–2′*. The E. M. F. acting on coil *b* will therefore be represented by *x–6′* equal and opposite to *x–5′*. Now, when the load is non-inductive, the current in coils *A* and *B* is in phase with the E. M. F.'s *x–1′* and *x–3′*, so that the E. M. F. acting on coil *a* is 30° behind the current in *A*, and the E. M. F. acting on *b* is 30° ahead of the current in *B*.

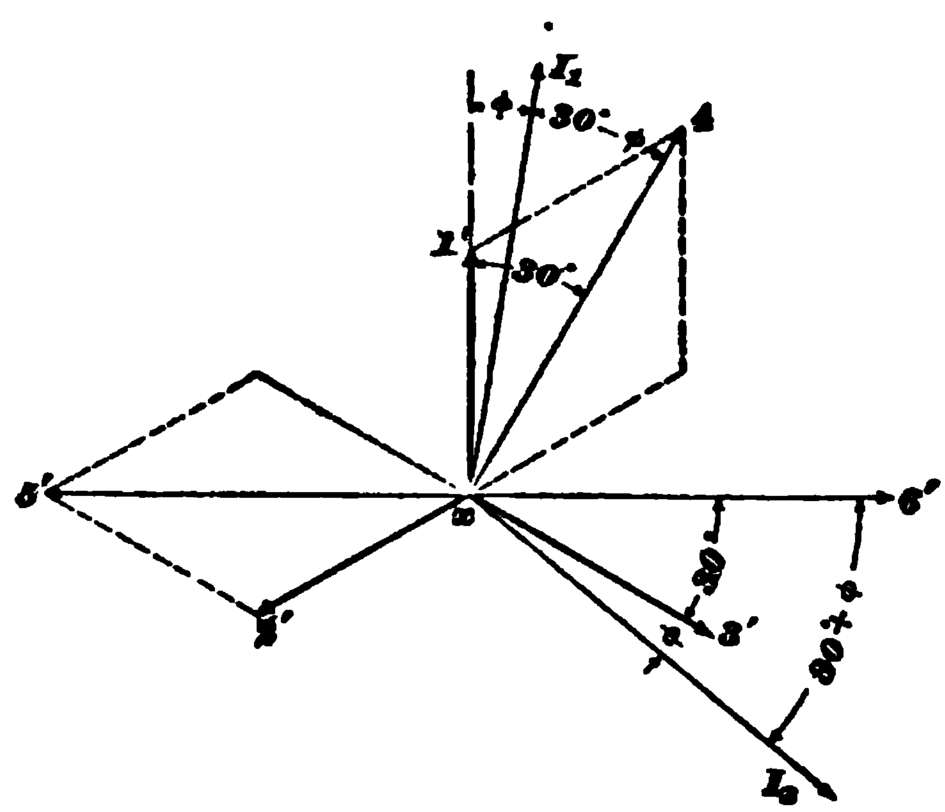


FIG. 55

If the load is inductive, the currents in the coils *A*, *B* instead of coinciding in phase with *x–1′* and *x–3′* will lag by an angle ϕ, cos ϕ being equal to the power factor of the load. The current will then be represented by the lines $x–I_1$ and $x–I_2$ lagging ϕ degrees behind *x–1′* and *x–3′*. Lines *x–4* and *x–6′* represent the E. M. F.'s applied to coils *a*, *b* so that with an inductive load the phase difference between the currents in *A* and *a* is 30° – ϕ, and between the currents in *B* and *b* it is 30° + ϕ. If we represent the pressures *x–1′*, *x–2′*, *x–3′*, etc. by ε, the pressure *x–4* or the line pressure will be $\sqrt{3}\,\varepsilon$. The watts indicated by *A* will be $\sqrt{3}\,\varepsilon I_1$ cos

$(30° - \phi)$, and the watts indicated by B, $\sqrt{3}\, \varepsilon\, I_s \cos (30° + \phi)$, and the sum of these two readings gives the power.*

60. It is now easily seen why a power factor of less than .5 will give a negative reading on one of the wattmeters. If the lag is 60°, the current in B differs in phase from that in b by $30 + \phi = 90°$; no effort is exerted on the swinging coil of the wattmeter and no deflection is given. If the lag becomes greater than 60° a torque is exerted in the reverse direction on the movable coil, and a negative deflection is obtained. For power factors greater than .5, both wattmeters will give positive readings, but their readings will not be alike and both positive unless ϕ becomes zero, i. e., unless the power factor is 100 per cent. or unity. If the angle of lag becomes 90°, both wattmeters will read alike, but one will be positive and the other negative, so that their sum will be zero. This is as it should be, because when the lag is 90° the current flowing in the circuit is wattless and no power is expended. The conditions under which the test is made will nearly always indicate whether or not a negative reading is to be expected. If there is any doubt on the matter, connect the meters to a load of lamps and after all connections have been made so that both meters read properly, take off the lamps and connect the load under test. If one of the meters gives a reverse reading it shows that the reading is negative and that the difference in the two readings must be taken to give the number of watts supplied. Fig. 56 shows the connections of a Wagner indicating

*That the sum of these two readings gives the power is easily shown for the case of a balanced circuit where $I_1 = I_s$. We have, power $= W = \sqrt{3}\, \varepsilon\, I_1 \cos (30° - \phi) + \sqrt{3}\, \varepsilon\, I_1 \cos (30° + \phi)$. From trigonometry we know that $\cos (30° + \phi) = \cos 30° \cos \phi - \sin 30° \sin \phi$, and $\cos (30° - \phi) = \cos 30° \cos \phi + \sin 30° \sin \phi$. Substituting these values for $\cos (30° + \phi)$ and $\cos (30° - \phi)$, we have

$$W = 2\sqrt{3}\, \varepsilon\, I_1 \cos 30° \cos \phi,$$

but $\cos 30° = \frac{\sqrt{3}}{2}$; hence, $W = 3\, \varepsilon\, I_1 \cos \phi$, but $\varepsilon\, I_1 \cos \phi$ is the power in one phase, and $3\, \varepsilon\, I_1 \cos \phi$ is the total power, so that the sum of the two wattmeter readings gives the total power supplied to the circuit.

wattmeter for measuring the watts on a three-phase circuit with balanced or unbalanced loads and with any power factor. It consists essentially of two wattmeters; *A A*, *A′ A′* are the two sets of current coils and *B*, *B′* the two movable potential coils mounted on the same shaft. The torque due to the two wattmeters is thus added or subtracted, as the case may be, and the pointer attached to the shaft indicates the actual number of watts expended. The current coils are supplied from current transformers, and each of the movable coils has a non-inductive resistance in series with it. This

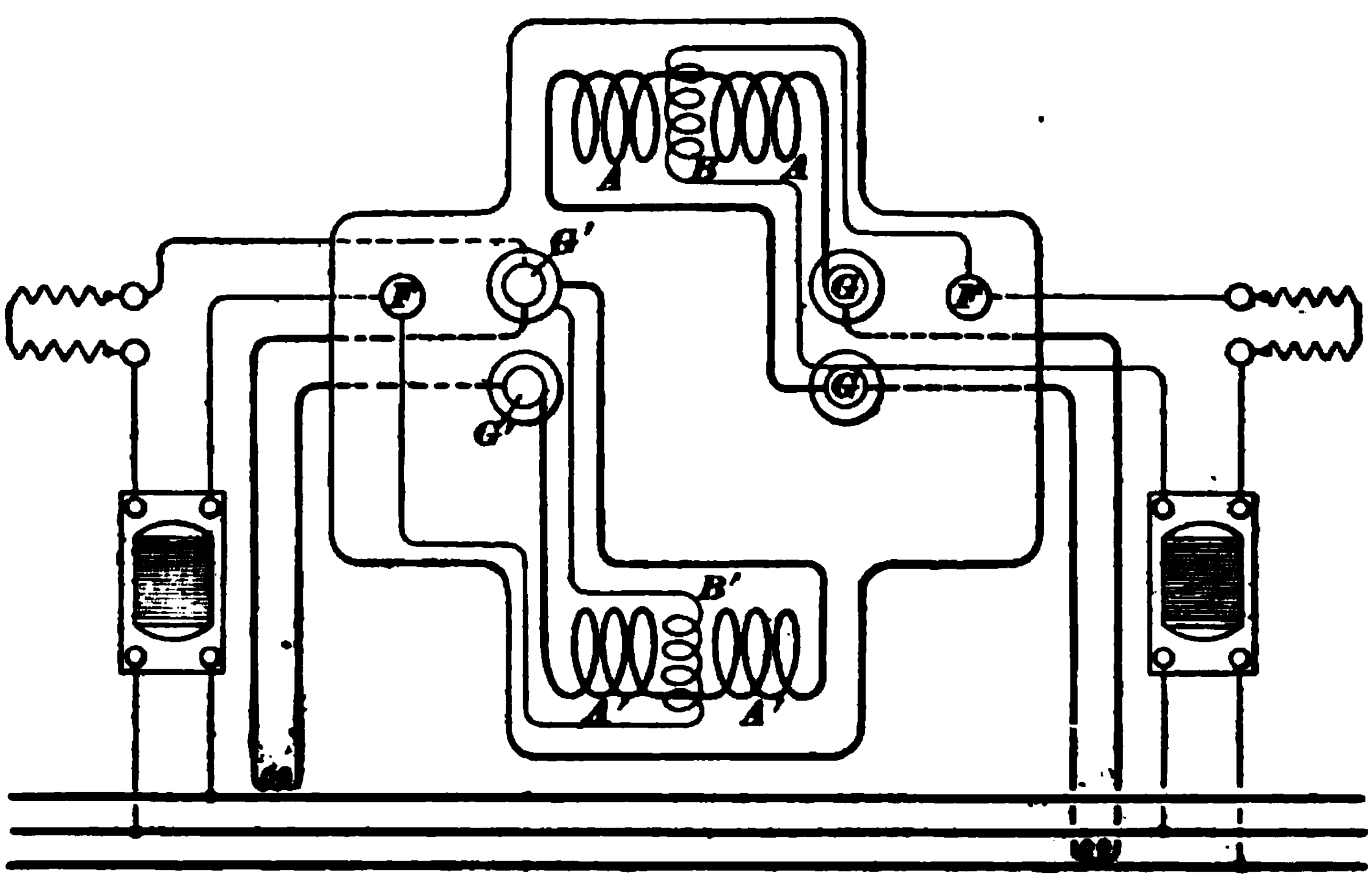


Fig. 56

wattmeter is also suitable for measurements on an unbalanced two-phase system.

The recording wattmeter, shown in Fig. 45, is used largely for measurements on three-phase circuits. Since the two wattmeter elements act on a common armature, if one of them gives a negative turning effort, the net turning effect on the disk is reduced and the record on the dial is due to the difference of the effects of the two wattmeters. The instrument, therefore, gives an accurate record, no matter what the power factor may be.

61. Measurement of Power Factor.—The fact that the ratio of the two wattmeter readings, Fig. 54, varies with the power factor of the load affords a method of determining the power factor from the wattmeter readings.* Of course if ammeter and voltmeter readings are available the power factor can be calculated, since it is equal to $\frac{\text{true watts}}{\text{apparent watts}}$ the true number of watts being obtained from the wattmeter readings and the apparent watts from the voltmeter and ammeter readings. For a three-phase circuit the apparent watts would be $\sqrt{3}\, E\, I$. When two wattmeters are used, as shown in Fig. 54, the power factor of a three-phase circuit can be determined from the ratio of the readings alone, and ammeter and voltmeter readings are not necessary. The ratio of the readings is

$$\frac{\sqrt{3}\ \varepsilon\, I \cos(30^\circ + \phi)}{\sqrt{3}\ \varepsilon\, I \cos(30^\circ - \phi)} = \frac{\cos(30^\circ + \phi)}{\cos(30^\circ - \phi)};$$

$$\frac{\cos(30^\circ + \phi)}{\cos(30^\circ - \phi)} = \frac{\cos 30^\circ \cos\phi - \sin 30^\circ \sin\phi}{\cos 30^\circ \cos\phi + \sin 30^\circ \sin\phi}$$

but $\cos 30^\circ = \frac{\sqrt{3}}{2}$, and $\sin 30^\circ = \frac{1}{2}$; hence,

$$\frac{\cos(30^\circ + \phi)}{\cos(30^\circ - \phi)} = \frac{\frac{\sqrt{3}}{2}\cos\phi - \frac{1}{2}\sin\phi}{\frac{\sqrt{3}}{2}\cos\phi + \frac{1}{2}\sin\phi} = \frac{\sqrt{3}\cos\phi - \sin\phi}{\sqrt{3}\cos\phi + \sin\phi}$$

Now if we take the expression $\frac{\sqrt{3}\cos\phi - \sin\phi}{\sqrt{3}\cos\phi + \sin\phi}$, and substitute different values for ϕ, we will get the ratio of the wattmeter readings corresponding to those values. For example, if $\phi = 60^\circ$ we have ratio of wattmeter readings

$$= \frac{\sqrt{3} \times \frac{1}{2} - \frac{\sqrt{3}}{2}}{\sqrt{3} \times \frac{1}{2} + \frac{\sqrt{3}}{2}} = \frac{0}{\sqrt{3}} = 0.$$ An angle of lag of 60° corresponds to a power factor of .5. For an angle of lag of

*E. J. Berg, Electrical World and Engineer, Vol. XXXIX.

30°, power factor = cos 30° = .866, we have ratio of readings

$$= \frac{\sqrt{3} \times \frac{\sqrt{3}}{2} - \frac{1}{2}}{\sqrt{3} \times \frac{\sqrt{3}}{2} + \frac{1}{2}} = \frac{1}{2}$$

By thus taking different values of the power factor we can plot a curve, Fig. 57, showing the relation between the ratio of the wattmeter readings and the power factor of the load.

EXAMPLE.—The power supplied to a three-phase induction motor is measured by means of two wattmeters connected as shown in Fig. 54.

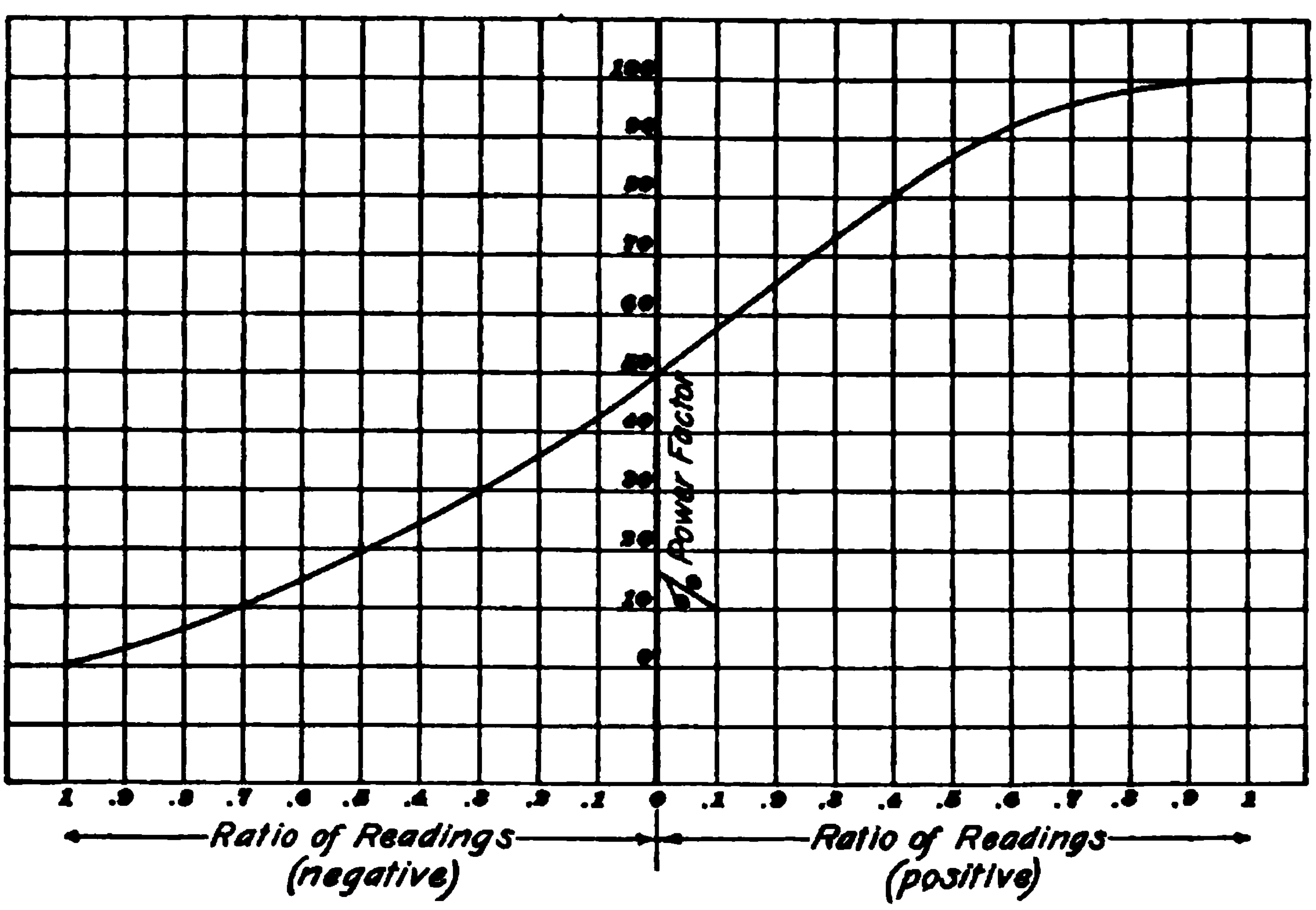


FIG. 57

The reading of A is 2,000 watts, and that of B 6,000 watts. What is the power factor of the motor corresponding to this load, and what is the total power supplied to the motor?

SOLUTION.—The ratio of the two readings is $\frac{2{,}000}{6{,}000} = .333$ and is positive, because both readings are positive. Hence, referring to Fig. 57, we take the ratio .333 on the right of the center line, and find that the power factor corresponding to this ratio is about .74. The total power supplied to the motor will be 2,000 + 6,000 = 8,000 watts.

62. Power-Factor Indicators.—The power-factor indicator made by the General Electric Company and used on

three-phase circuits is based on the foregoing principle. It consists of a fixed current coil, connected in series with the middle line, within which two potential coils are mounted on a vertical shaft. These coils are connected between the middle and outside lines. The resultant effort tending to deflect the shaft will evidently vary with the power factor, because the phase relation of the currents in the movable coils to the current in the fixed coil will change with the power factor and the instrument can be calibrated so that the pointer attached to the movable coils will indicate the power factor.

Another type of power-factor indicator that is commonly used is the same in construction as an indicating wattmeter,

Fig. 58

except that the potential coil is connected in series with an inductance so that the current in it is 90° behind the current in the main coils when the power factor is 1. The result is that with a power factor of 1 there is no deflection of the pointer because there is no torque action between the two coils. With a power factor less than 1, lagging current, the pointer swings in one direction and with a power factor greater than 1, leading current, the pointer swings in the other direction. Fig. 58 shows the front of a Wagner power-factor indicator operating on this principle.

63. Measurement of Power With One Wattmeter. The power supplied to a balanced three-phase load may be measured with a single wattmeter, as shown in Fig. 59, by

first taking a reading with the potential coil connected at *c* and then quickly transferring the connection to *c'*. The sum of the two readings will give the power if the power factor is over .5; if less than .5, the difference in the readings would

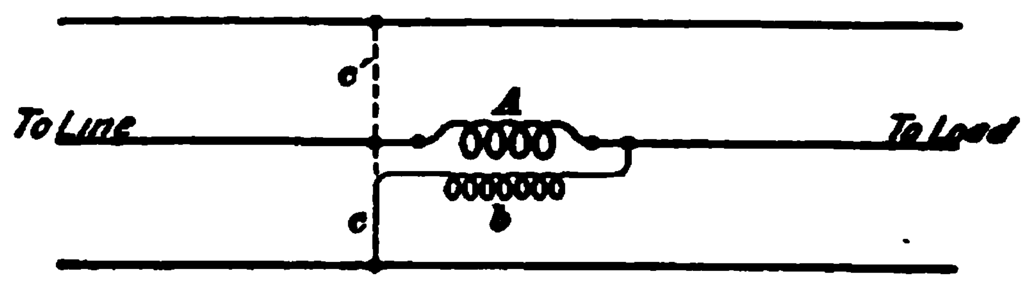


FIG. 59

be taken. It is necessary, however, to use two wattmeters unless the load can be kept constant while the connections are being changed or in case the load is not balanced.

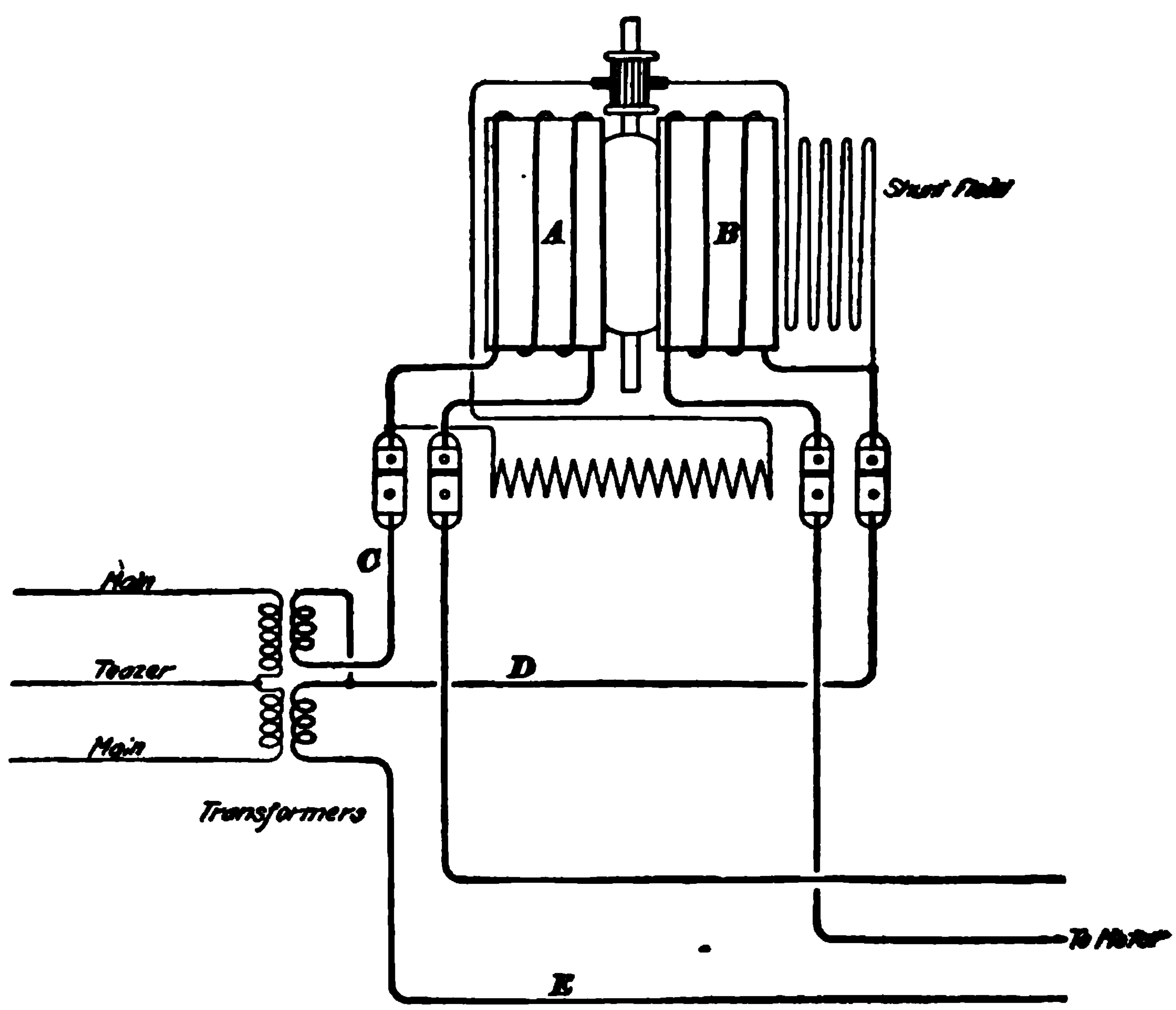


FIG. 60

64. Power Measurement on Monocyclic Circuit. Fig. 60 shows the connections for a Thomson recording wattmeter measuring energy supplied to a motor operated on the monocyclic system. The meter has two coils *A*, *B*,

which are connected in series with two of the lead wires running to the motor. As shown in the figure, the coils are in series with the leads *C*, *D*. If it is found that the speed of the meter diminishes when the load on the motor increases, field coil *A* should be connected in series with the main *E* instead of *C*.

INSTALLATION OF RECORDING WATTMETERS

65. Location.—Recording wattmeters should be located so that they can be easily reached either for the purpose of taking readings or inspecting them. They are too often placed in out-of-the-way places where they are very difficult to get at. They should not be placed in a position where they will be subjected to vibration as, for example, near a door that is continually being opened and shut. The location should be such that the meter will not be exposed to dampness or chemical fumes of any kind.

CONNECTIONS FOR METERS

66. The method of connecting meters to the circuit varies with the size and make of the meter. It is impossible to

FIG. 61

give here all the different connections and, moreover, it is not necessary or desirable to do so, as the makers send

FIG. 62

FIG. 63

out instructions with the meters, and these instructions are liable to change with changes in the construction of the meters. Therefore, only a few of the most common connections used on direct-current or single-phase alternating-current circuits will be described.

67. Connections for Thomson Recording Wattmeter.—Fig. 61 shows the method of connecting a Thomson recording wattmeter of small capacity on a two-wire circuit.

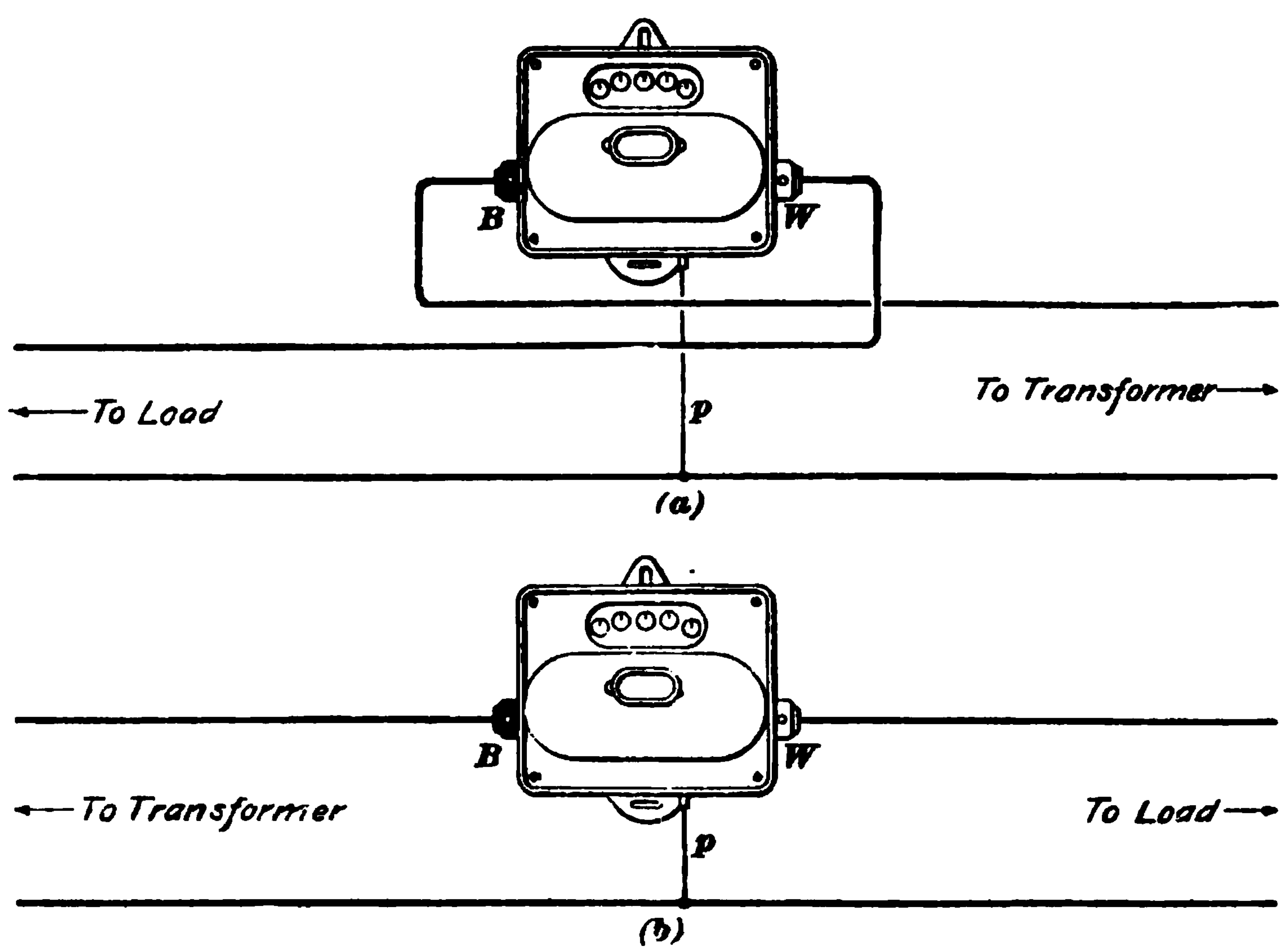


FIG. 64

When the meter is of large capacity, only one side of the circuit is run through it and a small potential wire is run in from the other side, so as to put the armature across the circuit. This method of connection is shown in Fig. 62. Fig. 63 shows a meter connected to a three-wire circuit.

68. Connections for Stanley Induction Wattmeter. Fig. 64 (*a*) and (*b*) shows the methods of connecting a Stanley wattmeter. The black terminal *B* on the meter must always connect to the transformer or other source of

E. M. F. The white terminal *W* connects to the load. It is necessary to have these connections correct or the meter will not rotate in the proper direction. The potential wire *p* connects from the meter to the wire that does not enter the meter.

The connections for induction wattmeters are much the same no matter what the make may be, the current coil or coils being connected in series with the circuit, and the potential coil across the circuit. What differences there may be are due to the manner in which the leads are brought

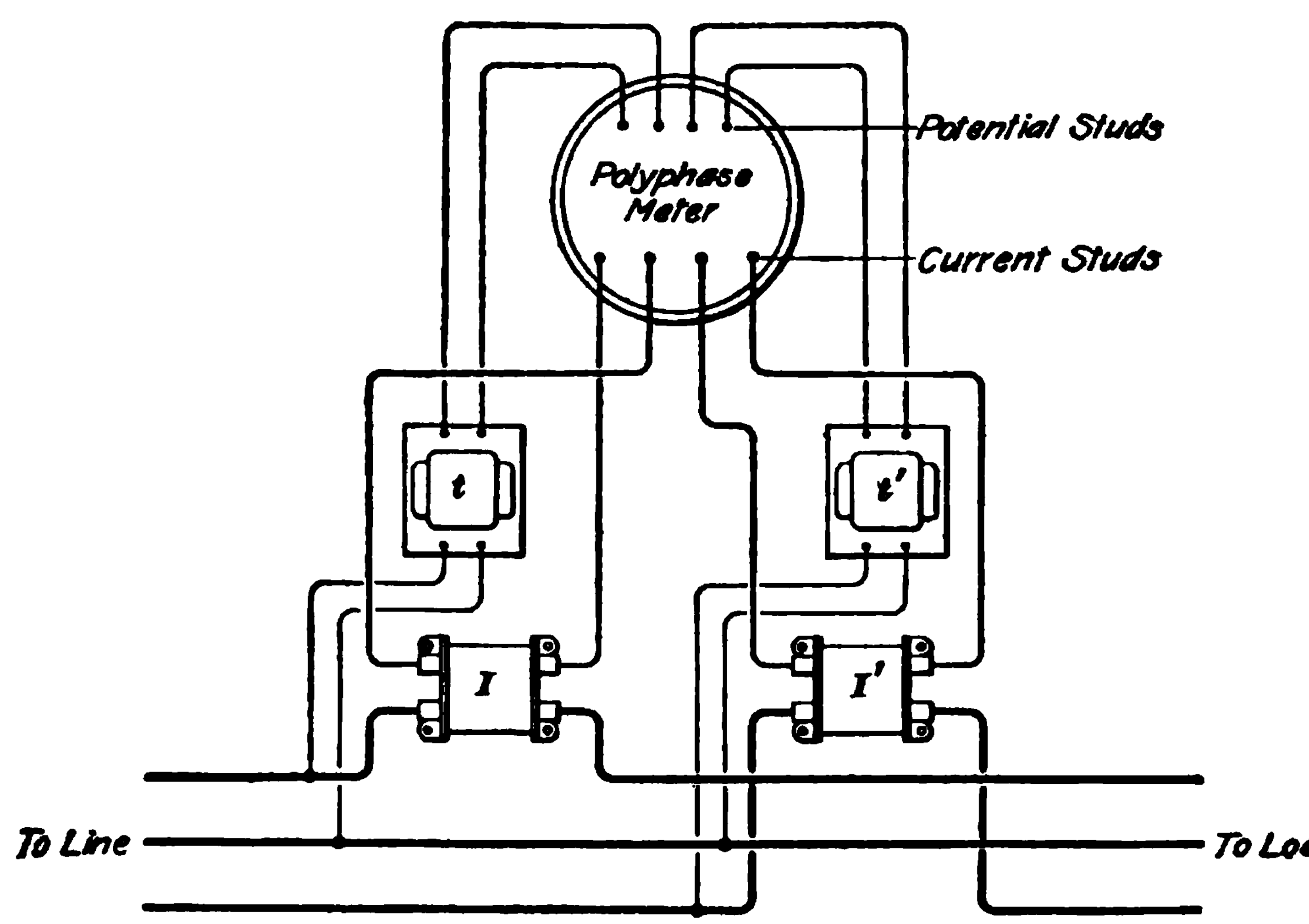


Fig. 65

out of the meter case. In most cases current transformers are used in connection with meters on high-tension lines, the current coils being connected in series with the secondary of a current transformer instead of in series with the main circuit. On high-potential circuits, the potential coils are supplied from potential transformers that step-down the voltage applied to the coils. Of course, when current and potential transformers are used in connection with a meter, the instrument is always calibrated so that it will take account of the current or voltage transformations and

indicate the number of watts in the main circuit. Fig. 65 shows the connections for a General Electric induction wattmeter of the polyphase type used on switchboards. In this case, potential transformers t, t' are used to step-down the voltage and current transformers I, I' to transform the current. The connections shown are such as would be used on a three-phase circuit or a three-wire, two-phase circuit with the common return wire in the middle.

TESTING AND ADJUSTING RECORDING WATTMETERS

69. Recording wattmeters should be checked up occasionally to see if they record correctly. If a rough test only is required the meter may be loaded with a specified number of lamps of which the power consumption per lamp is known; if a more accurate test is desired, the recording

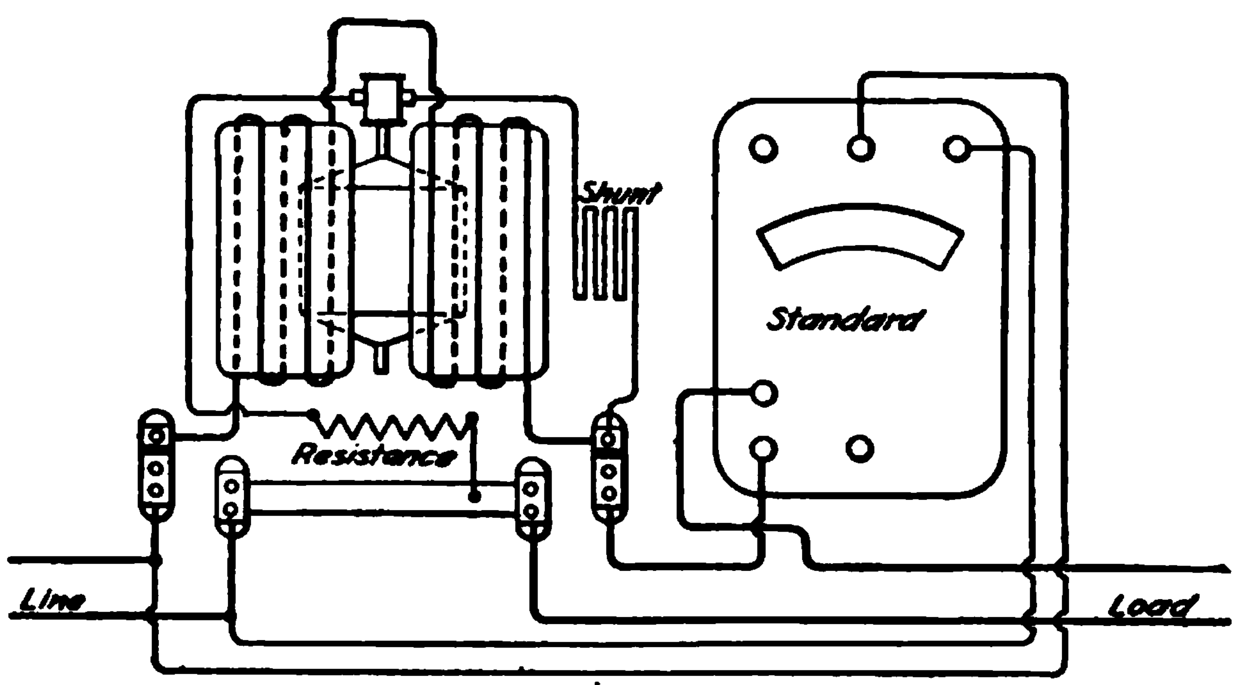


FIG. 66

meter is usually checked by comparing it with a standard indicating wattmeter.

70. Checking a Thomson Recording Wattmeter. Figs. 66 and 67 show connections for checking a two-wire Thomson meter. Either set of connections may be used. The meter is set to work on a load of lamps, or other convenient resistance, the standard direct-reading wattmeter

being connected as shown. A chalk mark is made on the meter disk, so that the revolutions may be easily counted, and the revolutions are taken for 40 to 60 seconds, the observer using a stop-watch. Another observer reads the standard instrument, and the load is kept as nearly constant as possible throughout the test. The meter watts may then be calculated from the following formula:

$$\text{Meter watts} = \frac{3{,}600\,R\,K}{T} \qquad (1)$$

where R = number of revolutions in T seconds;
T = time in seconds of R revolutions;
K = constant of meter.

The constant K used in formula **1** was, in the older types of meter, marked on the dial and was a number by which the dial reading had to be multiplied to give the true reading

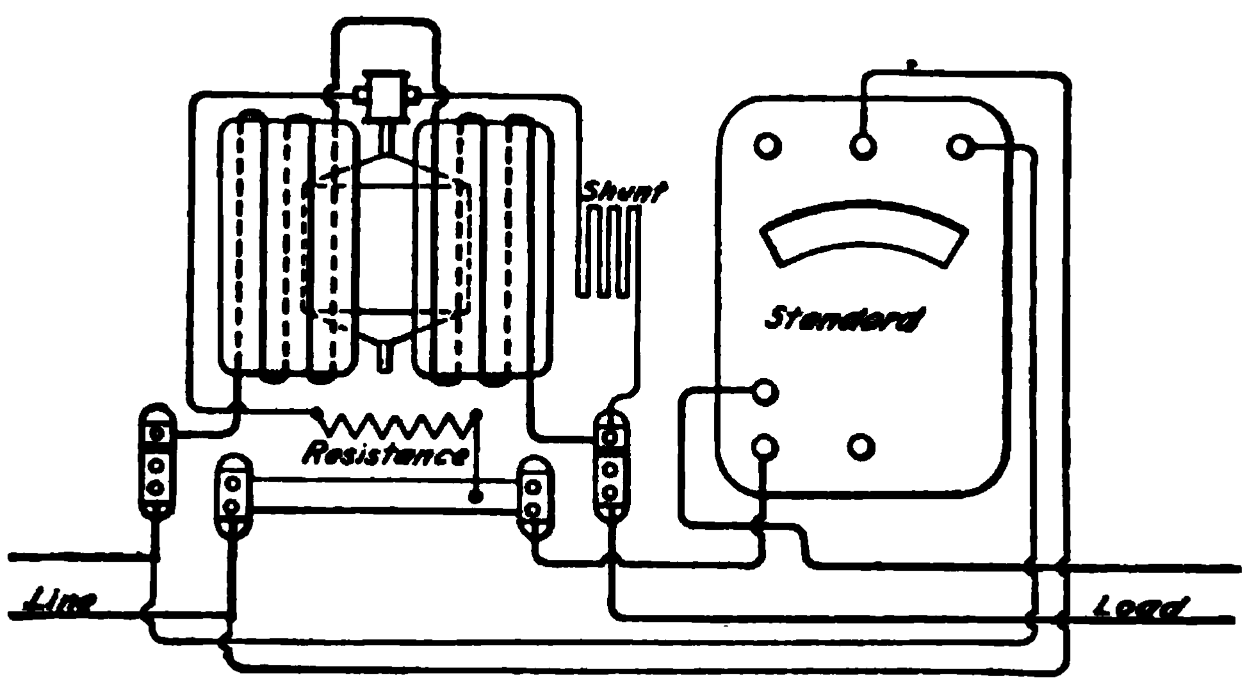


FIG. 67

of the meter. In recent types of Thomson meter, the gears in the recording train are arranged so that the dial reads directly and no constant is marked on it except in meters of large capacity. In recent meters the constant K used in formula **1** will be found marked on the revolving disk.

The actual watts are obtained from the standard meter; hence, the percentage by which the meter is correct is found by dividing the number of watts given by formula **1** by the number of watts given by the standard meter.

EXAMPLE.—The disk of a 10-ampere, 100-volt Thomson meter makes 10 revolutions in 60 seconds. The average number of standard watts as indicated by the standard meter is 303. Find the percentage error of the recording meter. The constant of the meter is $\frac{1}{2}$.

SOLUTION.—From formula **1**, we have

$$\text{Meter watts} = \frac{3{,}600 \times 10 \times \frac{1}{2}}{60} = 300$$

$$\frac{300}{303} = .99, \text{ or } 99\%. \quad \text{Ans.}$$

The meter is, therefore, 1 per cent. too slow, and the damping magnets should be shifted in a little so that the retarding action on the disks will not be so great.

71. If a standard wattmeter is not available for testing purposes, separate ammeters and voltmeters may be used for direct-current work, but they are not as convenient.

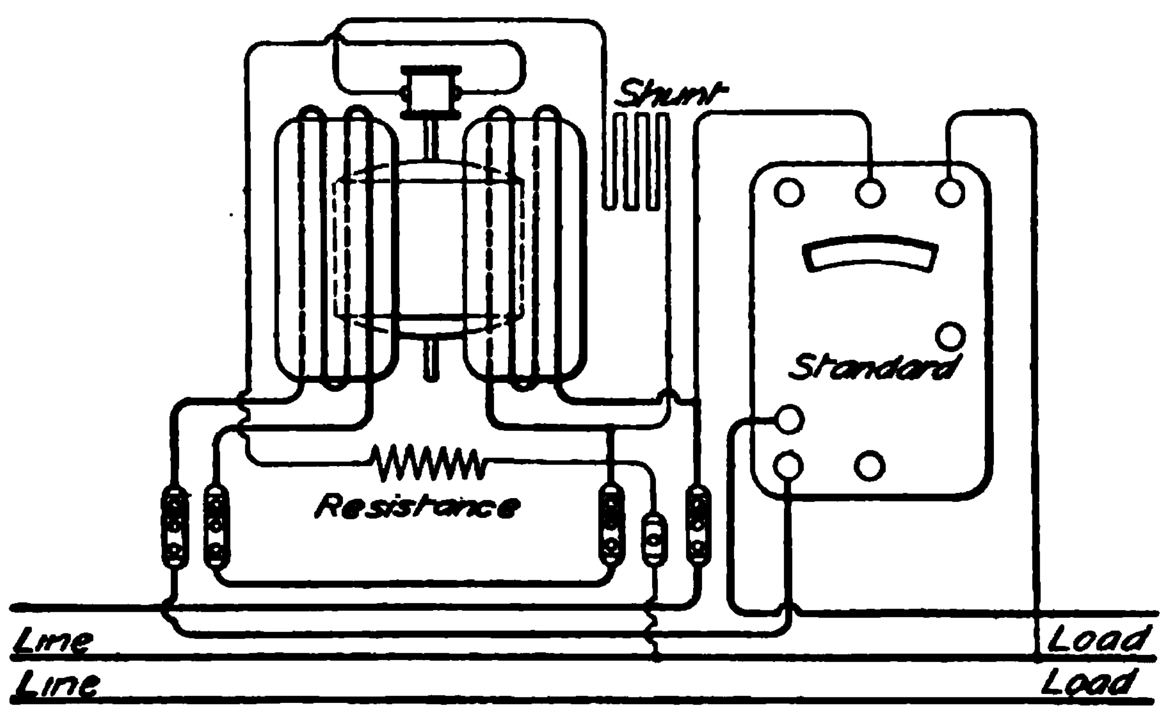


FIG. 68

In Figs. 66 and 67 it will be noticed that the energy consumed by the potential circuit of either meter is not measured by the other; that is, the current in the armature of the Thomson meter does not pass through the fields of the standard meter, neither does the current in the shunt of the standard pass through the field coils of the Thomson meter.

To test a Thomson meter used on a three-wire circuit (110–220 volts), the connections may be made as shown in Fig. 68. The potential circuits are wound for 110 volts. The field coils can, therefore, be connected in series, and the standard meter connected as shown. In formula **1**, however,

K should be taken as one-half the constant marked on the dial or disk. Aside from this, the meter can be tested in the same manner as a two-wire meter.

72. Checking a Stanley Wattmeter.—Fig. 69 shows the connections for checking a Stanley wattmeter and the connections for testing any two-wire induction wattmeter

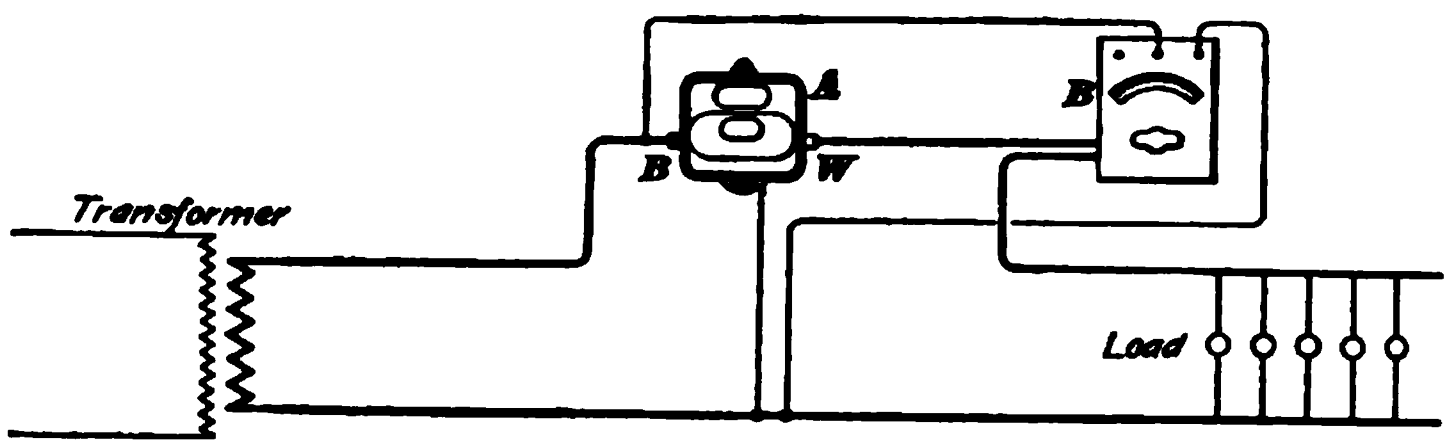


FIG. 69

would be very similar. A is the recording wattmeter and B the standard instrument. With the Stanley meter the watts are given by the following formula:

$$\text{Meter watts} = \frac{100\,R\,K}{T} \qquad (2)$$

where only R = number of revolutions in T seconds;
T = time in seconds for R revolutions;
K = a constant marked on the meter case.

This formula applies also to the Fort Wayne induction meters, the values of K being given for different sizes of meters, in a table furnished by the manufacturers.

READING RECORDING WATTMETERS

73. The dials of most wattmeters record either watt-hours or kilowatt-hours. In some cases, as with the earlier types of Thomson meter, the reading taken from the meter dials must be multiplied by a constant in order to obtain the watt-hours. This constant is usually marked on the dial. However, the general practice now is to make the dials of meters direct reading except in the case of meters of large capacity. If no constant is marked on the dial it can be assumed that the meter is direct reading.

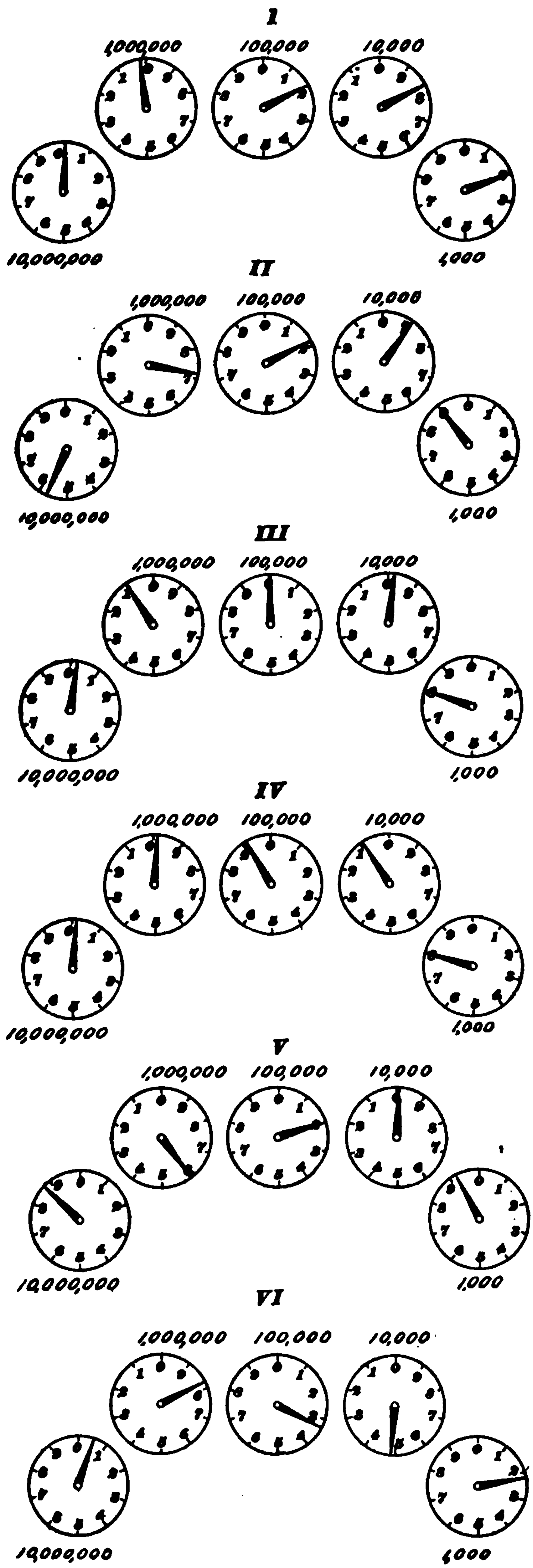

I
1,000,000
100,000
10,000
10,000,000
1,000
II
1,000,000
100,000
10,000
10,000,000
1,000
III
1,000,000
100,000
10,000
10,000,000
1,000
IV
1,000,000
100,000
10,000
10,000,000
1,000
V
1,000,000
100,000
10,000
10,000,000
1,000
VI
1,000,000
100,000
10,000
10,000,000
1,000

Fig. 70

74. Reading Thomson Meter.—The Thomson meter has five dials. The lowest reading pointer is the one to the extreme right (facing the meter); it is marked 1,000, which means that one complete revolution of the hand indicates 1,000 watt-hours, and that each division therefore represents 100 watt-hours. The next one to the left is 10,000 to a revolution, or 1,000 for a division, and so on. Fig. 70 shows six different readings, by studying which the student should be able to take readings from any meter.

Beginning at the left, number the pointers 1, 2, 3, 4, and 5. Then, in *I*, Fig. 70, pointer 5 is on *2* and is read 200. Pointer 4 is two-tenths of the way between *8* and *9* and is read 8,000. Pointer 3 is read 10,000. Pointer 2 has not gone through its first division; likewise pointer 1. The statement is then 18,200.

The statement of *II* is 5,718,900 (not 5,719,900, as it frequently would be read). Pointer 4 should not be read *9* until pointer 5 has completed its revolution and is again at *0*.

The statement of *III* is 99,800 (not 109,800), because the 100,000 mark will not be reached until pointer 5 has passed from *8* to *0*, when 4 and 3 will be at *0*, pointer 2 at *1*, and pointer 1 just past the zero mark.

The statement of *IV* is 9,990,800. Pointer 1 is slightly misplaced. Otherwise, the reasons given above will apply to this statement.

The statement of *V* is 8,619,900. Pointer 2 is misplaced. It should be two-tenths of the way between *6* and *7* instead of nearly over *6*, as shown.

The statement of *VI* is 834,200. Pointer 4 is misplaced. It should be two-tenths to the right of *4* instead of to the left of *5*. These misplaced hands are frequently met with in practice and are generally caused by a knock in removing the cover, or, perhaps, they are a little eccentric.

Rule.—*To ascertain the number of watt-hours that has been used by a consumer from one date to another, subtract the earlier statement from the latter and multiply by the constant of the meter, if one is marked on the dial. In case no constant is*

marked on the meter, the constant is 1, and the readings are taken as given by the dial.

EXAMPLE.—An electric company supplies power to operate a motor for one of its customers. The rate charged is 5 cents per kilowatt-hour. The reading of the meter on January 30 is 8,619,900, and on February 28, it is 9,990,800. The constant of the meter is 2. What should be the amount of the bill for the month?

SOLUTION.—The number of watt-hours supplied between Jan. 30 and Feb. 28 = (9,990,800 − 8,619,900) × 2 = 2,741,800.

2,741,800 watt-hours = 2,741.8 K. W.-hours, which at 5 cents per K. W.-hour would amount to 2,741.8 × .05 = $137.09. Ans.

SPECIAL METERS

75. The Two-Rate Meter.—Most electric-light stations have their period of heaviest load for a few hours only in the evening. During the daytime the plant is lightly loaded, and a large part of the machinery is standing idle. In order

FIG. 71

to obtain a *day load* and thus work the plant to best advantage, some companies supply power during the daytime at specially low rates in order to induce customers to use electric motors. For measuring the power supplied to such

customers, *two-rate meters* are sometimes used. A **two-rate meter** is one that records the power during certain hours of the day at a rate different from that at other hours. One of the earlier types made by the General Electric Company was a regular Thomson recording meter provided with two dials and recording trains, which were arranged so that a self-winding clock would throw either one or the other into gear with the meter shaft at the proper time. The energy recorded on the two dials was then charged for at different rates.

In the later type of General Electric two-rate meter an ordinary Thomson meter *A*, Fig. 71, with a single dial is used. Connected to the potential circuit of *A* is a self-winding clock mechanism contained in the case *B*. The case also contains a resistance, which, during certain hours, is inserted in series with the armature of the wattmeter, thus making the meter run at a reduced speed during those hours. The two-rate attachment, therefore, makes the meter run slow during certain hours, which is equivalent to charging for the power at a low rate during those hours.

76. Maximum-Demand Meter.—The maximum amount of current that the various customers consume determines in large measure the capacity of the station equipment. Some customers might use large currents for short intervals only, but the plant must be capable of handling these large currents; in some cases, therefore, the maximum demand for current is taken into account in making up the bill; for example, all current over a certain amount is charged for at a higher rate. One style of instrument used for indicating the maximum current used above a certain amount is the *Wright maximum-demand meter*, shown in Fig. 72. It consists of a **U**-shaped tube, hidden partly by the scale in the figure, which has bulbs *A*, *B* on either end; a branch tube *C* is attached near *B* and carried down over the scale. The lower end of tube *C* is closed. The current flows from *D* to *E* through the resistance strip *F* coiled around bulb *A*. The tube is partially filled with liquid, which remains in it as long

as the current does not exceed a certain amount. If, however, the current exceeds the allowable amount, the expansion of the air in A due to the heating of strip F will force liquid into the tube C. Any increase in the current will force

Fig. 72

over more liquid, and from the height of the column of liquid in tube C the charge can be estimated. The U-shaped tube is mounted on an arm that can be swung up after the reading has been taken, thus emptying tube C into the U-shaped tube.

INDEX

NOTE.—All items in this index refer first to the section (see the Preface) and then to the page of the section. Thus, "Alternator brushes, §21, p56," means that alternator brushes will be found on page 56 of section 21.

U

V

W